EVALUATION OF EMISSIONS REDUCTION STRATEGIES FOR HEAVY DUTY DIESEL CONSTRUCTION EQUIPMENT

By

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EVALUATION OF EMISSIONS REDUCTION

STRATEGIES FOR HEAVY DUTY DIESEL

CONSTRUCTION EQUIPMENT

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I would like to dedicate my dissertation to my lovely husband. This long and challenging journey was not possible without his help and support.

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Abstract:
Heavy-duty diesel (HDD) construction equipment expends a considerable amount of fuels and correspondingly emits a substantial amount of pollutants to the air. This dissertation assesses potential impacts of diesel exhaust on operator and investigates some emission reduction strategies for HDD construction equipment based on real-world in-use data. Second-by-second data for fuel use and emission rates of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and particular matter (PM) as well as engine attributes were collected from 32 HDD construction equipment using Portable Emission Measurement Systems (PEMS).

First, the impacts of tailpipe diesel exhaust emissions on Indoor Air Quality(IAQ) in heavy equipment cabs were characterized. The working hypothesis for this objective was tailpipe pollutant concentrations of NO_x, CO, CO_2, and PM exceed industry Permissible Exposure Limit (PELs). Based on the results, tailpipe emissions of NO_x, CO, and CO_2 greatly exceed their respective PEL (or reasonable surrogate). In some cases, the limit was exceeded by orders of magnitude.

Therefore, some emission reduction strategies were investigated to improve IAQ in heavy equipment cabs. Using the same real world data, statistical comparisons of B20 versus petroleum diesel fuel use were performed on a fleet of backhoes, motor graders, and wheel loaders. Results show that B20 had a non-significant higher average price per gallon, as well as a significantly higher average hourly fuel use rate than petroleum diesel; however, B20 had significantly lower average emissions of NO_x, HC, CO, and CO_2 on a gram per gallon basis.

Then, the energy and environmental impact of engine tier standards (tier 0 vs. tier 1 vs. tier2) were assessed. Based on the results, the major conclusion is that there are measurable differences in the impacts of higher tier number when used in off-road maintenance equipment. Overall, we can see an improvement in emission rates in more than 60% of cases, when higher tier number was concerned. Fuel use decreases as well in almost all cases with higher tier number. So, the general conclusion is that higher tier number has a positive environmental impact based on reductions in emissions of NO_x, HC, CO, and CO_2 on a grams per gallon and gram per hour basis as well as fuel use on a gram per hour basis.

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CHAPTER I

INTRODUCTION

1.1. Motivation

Heavy Duty Diesel (HDD) operators are one group exposing in the harmful situation every day. HDD equipment operators work in cruel conditions several hours a day in extreme temperature and humidity and dusty environment. They work very close to the tailpipe as a pollutant source (Figure1). It is assumed that tailpipe emissions concentrations will be diluted in outdoor air, however, because of the close proximity of the tailpipe to the cab, some pollutants enter into the cab and result in poor IAQ for the operator. Therefore, proper emissions reduction strategies have to be applied in order to diminish harmful exhaust effects.

Figure 1. Heavy Duty Diesel (HDD) Equipment Operator Work Condition

Some research has been done on tailpipe emission penetration to cabin and showed tailpipe emission is the main source of passenger exposure to diesel-related pollutants. Another significant finding was that almost all diesel-related pollutant exposures were due to the time spent commuting on the bus and not the time spent at bus stops or loading and unloading students. (“Fact Sheet”,2003). This study shows the significance of studies on emissions reduction strategies for HDD equipment operators.

This issue will get more significant as the number of HDD equipment operators grow annually at a rate of 19% which is faster than the national average for other occupations. It means 500,000 operators are in danger of exposing to diesel-related pollutants in 2022 (“Construction Equipment Operators”, 2016).

Another motivation for this research is due to ”dieselgate” or Volkswagen emissions scandal. Volkswagen who has 70 percent of U.S. passenger-car diesel market constantly advertised “Clean Diesel” as a proper substitute for electric and hybrid vehicles. However, cheating on diesel-emission tests is a big accusation for a prestigious company like Volkswagen (“Everything You Need to Know about the VW Diesel-Emissions Scandal”, 2017).

Emission software was installed by Volkswagen on 11 million cars worldwide including half a million in the U.S. In 2014. A group of scientists at West Virginia

University has been granted $50,000 to conduct tests on three diesel cars: a VW Jetta, a VW Passat, and a BMW X5 (Franco, Sánchez, Posada., German, & Mock, 2015).

Two professors and two students used a portable emissions measurement system (PEMS) to test emissions from these three diesel vehicles under real-world conditions. They collected driving emissions data and compared them with laboratory dynamometer testing (West Virginia researcher describes how Volkswagen got caught, 2017).

During the test, researchers found that Jetta exceeded U.S. emissions limits up to 35 times and Passat up to 20 times under real-world driving conditions (Thompson, Carder, Besch, Thiruvengadam, &Kappanna, 2017)

After an investigation, they figured out that software sensed when the test starts, so it activated equipment to reduce emissions. However, it turns the equipment down during normal driving and increases emissions beyond legal limits set by the Environmental Protection Agency (EPA). The emission rate can be up to 40 times above the federal limit depending on driving style and load (“How Volkswagen’s ‘Defeat Devices’ Worked”,2017). This dieselgate scandal can alert environmental advocate about possible cases in other vehicles including HDD construction equipment and motivates us to do more investigation about possible emission rates issues in construction jobsites.

1.2. Background

International Agency for Research on Cancer and the U.S. Environmental Protection Agency (EPA) has categorized diesel exhaust as a potential human carcinogen. Studies show that rats exposing to high levels of diesel exhaust are in higher risk of lung tumors and humans frequently exposing to diesel fumes got lung cancer. Occupational health studies of railroad, dock, trucking, and bus garage workers show that routinely exposing to high levels of diesel exhaust over many years increases lung cancer or mortality risk by 20 to 50 percent ("Health Assessment Document", 2002).

This research is very important since DE exposure is a crucial human health issue. EPA assessed the possible health hazards associated with diesel pollutant exposure and concluded that DE has short-term and/or acute exposures effects as well as long-term chronic exposures. Operating heavy equipment may include any of these exposures. There is enough evidence to show that diesel pollutants can cause acute and chronic health effects according to the EPA statement. Eyes, nose, throat and lungs irritation, coughs, nausea, asthma, and neurological effects like lightheadedness are some examples of acute exposure("Health Assessment Document", 2002). These health effects lead to lost work days for heavy equipment operators, which decreases construction productivity.

The Occupational Safety and Health Administration (OSHA) does not have specific standards for diesel-related pollutants from heavy equipment; however, they do have

Permissible Exposure Limits (PEL) for many of the constituent pollutants found in diesel exhaust. These constituents include carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen oxides (NO_x) including NO and NO_2. Diesel particulate matter (PM) is not specifically regulated by OSHA but it is included in the PEL for Total Dust (“Diesel Exhaust”,2016).

Diesel-powered vehicles and equipment emit half of the nitrogen oxides (NO_x) and more than two-thirds of particulate matter (PM) in the US transportation system. Particular matter or soot are resulted from incomplete combustion of diesel fuel. There are hundreds of chemical elements in particular matter such as sulfates, nitrates, elemental carbon, ammonium, condensed organic compounds, carcinogenic compounds, and heavy metals like arsenic, selenium, cadmium, and zinc (“Particulate Matter”,1997)

Particular matter size varies from ultrafine particulates (less than 0.1 microns diameter) to fine particulates (less than 2.5 microns diameter) to coarse particulates (less than 10 microns diameter). Ultrafine particulate makes up 80-95% of diesel soot pollution and can easily penetrate lungs cells because of their small size. They annoy nose, the eyes, lungs, and throats and sometimes cause respiratory and cardiovascular illness and even immature death.

CO_2 is best known as a greenhouse gas emitted from the combustion of fossil fuel; however, it is also a common pollutant. Exposure to high levels of CO_2 results in symptoms ranging from headache to unconsciousness to death. The OSHA PEL for CO_2 in the construction industry is 5,000 parts per million (ppm) as an 8-hour time weighted average (8-hr TWA) ("Carbon Dioxide", 2016)

CO is a colorless and odorless toxic gas. At lower levels of exposure, CO causes mild effects including headaches, dizziness, disorientation, nausea, and fatigue – all of which may adversely affect the performance of heavy equipment operators and cause jobsite safety hazards. The effects of CO exposure vary depending on the concentration and length of exposure and ultimately lead to decreased worker productivity and lost work days. The OSHA PEL for CO in the construction industry is 50 parts per million (ppm) as an 8-hr TWA ("Carbon Monoxide",2016).

NO_2 irritates the eyes, nose, throat, and respiratory tract. High-dose exposure to NO_2 can contribute to Pulmonary edema and diffuse lung injury. Continued exposure to high levels of NO_2 can develop acute or chronic bronchitis. Exposing to a low level of NO_2 can increase bronchial reactivity and respiratory infections risk as well as decrease lung function. The OSHA PEL for NO_2 in the construction industry is 5 ppm as an 8-hr TWA with a ceiling of 9 mg/m^3 ("Carbon Monoxide", 2016).

Respirable particulate matter (PM) irritates eye, nose, and throat and causes respiratory infections and bronchitis as well as lung cancer. Construction sites have at least two sources of PM – dust and diesel particulate matter. These two types of PM are included in particles not otherwise regulated by OSHA and are known as Total Dust. The OSHA PEL for Total Dust is 15 mg/m^3 as an 8-hour TWA ("Nitrogen dioxide", 2016).

1.3. Scope of Work

A comprehensive real world and quality assured dataset was obtained from prior research conducted by Lewis (2009) about construction equipment emissions. This data is for NO_x, HC, CO, CO_2, and PM emission rates of tailpipe based on mass per time (grams per second) and a mass per fuel used (grams per gallon). One hundred forty hours of second-by-second data from 38 construction equipment was gathered. The equipment includes: (8) backhoes, (6) bulldozers, (3) excavators, (3) generators, (1) skid steer loader, (6) motor graders, (3) off-road trucks, (3) track loaders, and (5) wheel loaders. Corresponding data for engine performance parameters like intake air temperature (IAT), manifold absolute pressure (MAP), and revolutions per minute (RPM) are available. This data allows us to characterize the relationship between equipment engine activity and tailpipe emissions and investigate different emission reduction strategies using real world data. A summary of engine attributes is shown in Appendix K.

1.4. Objectives

Three sub-questions guided this study. The research objectives can be stated more precisely as the following:

1.4.1. Assess Potential Impacts of Diesel Exhaust on Operator

The Environmental Protection Agency identifies Indoor Air Quality (IAQ) as one of the five most urgent risks to public health (“Indoor Air Quality. The Inside Story: A Guide to Indoor Air Quality”, 2016). Given that heavy equipment operators spend most of their workday inside of the equipment cab, poor IAQ may be a significant health issue for them. This case study presents an analysis of real-world pollutant concentration data from five wheel loaders in order to compare them with commonly used permissible exposure limits. The pollutants included nitrogen oxides, carbon monoxide, carbon dioxide, and particulate matter.

1.4.2. Assess the Energy, Economical, and Environment Impacts of Alternative Fuels

There is a common belief that using biofuels instead of petroleum products can significantly decrease emission rates of HDD equipment in construction. But, further research is required to investigate this claim. The economic, energy, and environmental impacts of biodiesel versus petroleum diesel in off-road maintenance equipment were comparatively analyzed. Since biodiesel is made from a diverse mix of feedstocks, Minitab software was utilized to statistically analyze the dataset using t-test technique to examine how biofuels can affect fuel prices, fuel use rates, and emissions rates.

1.4.3. Assess the Energy and Environmental Impact of Engine Tier Standards (Tier 0 vs. Tier 1 vs. Tier2)

The increasing interest in upgrading engine tier has heightened the need for assessing engine tier impact on emission rates and concentration. Using Minitab software and our dataset, one-way ANOVA-Tukey test was conducted to evaluate the effectiveness of engine tier standards on emission reduction and fuel use in construction.

Also, the second task will be comparing pollutant emission rates to EPA standards for petroleum diesel bulldozers, track loaders, and motor graders.

1.5. Dissertation Layout

This dissertation is structured as follows:

Chapter one provides some motivation and background to justify our work along with its scope. Chapter two reviews other studies have been done in this area of research. Chapter three provides an account of methods were used to investigate the objectives. Chapter four describes the results based on analysis of equipment. Chapter five concludes with results. And last but not least, chapter six recommends future works to address another niche.

CHAPTER II

LITERATURE REVIEW

Indoor Air Quality (IAQ) is considered as one of the five most urgent risks to public health by the Environmental Protection Agency (EPA). IAQ in heavy equipment must be characterized in order to determine the severity of the problem in construction job sites. Also, there are plenty of suggestions to use alternative fuels and updated tiers to decrease emission rates and fuel use in HDD equipment. This chapter provides an overview of aforementioned studies related to HDD equipment.

2.1. Assess Potential Impacts of Diesel Exhaust on Operator

The faster growing rate of HDD equipment operators than the national average for other occupations makes it more important to do more assessment in HDD operator's exposure to emissions. These studies are categorized into two major groups: IAQ studies and equipment emission studies. Then, each group is divided into more sub-groups in order to facilitate summarizing studies that have been done previously in this area.

2.1.1 IAQ Studies

Some studies have been done on Indoor Air Quality to show its effect on drivers and commuters. They can be categorized into three major sub-groups: bus school studies, filtration system evaluation, and the assessment of heavy-equipment operators' exposure to emissions.

Previous research on children's exposure to diesel related pollutants in school buses provided compelling evidence that there may be a concern for equipment operator's exposure to diesel-related pollutants (Dennis *et al*., 2003). The Children's School Bus Exposure Study was conducted to assess the range of children's exposures to diesel-related pollutants during their commutes to school by diesel school buses. The study, conducted by researchers at the University of California Riverside and Los Angeles, measured pollutant concentrations of multiple diesel vehicle-related pollutants inside five conventional diesel school buses over real-world school bus routes in Los Angeles. The study measured exposures inside the buses but did not include tailpipe emissions.

Another type of studies has been done to evaluate the strategy of mitigating emissions effects using a filtration system. Organiscak, Cecala & Noll (2015) have done a study to show how two-instrument particle counting is a reliable method to measure cab filtration system performance.

Cecala *et al*. (2005) showed that two key components are necessary in order to keep operators safe from dust: effective filtration and cab integrity. So, they modified the drill's filtration and pressurization system in order to improve its design and performance and get a 93.4% efficiency for cab.

Moyer, Heitbrink & Jensen (2005) have conducted a study and showed The Met One or an identical optical particle counter is a reliable method to test enclosed cab filtration systems in order to evaluate filtration system integrity during maintenance.

Hansen (2013) developed a diesel exhaust exposure assessment for an elemental phosphorous plant. Thirteen samples were collected and analyzed during the study. Statistical analysis showed that nitrogen dioxide time weighted average levels can predict diesel particulate matter, but carbon monoxide time weighted average measurement cannot predict of diesel particulate matter precisely. Workplace exposure to diesel particulate matter, carbon monoxide and nitrogen dioxide must be directly measured and extrapolation from indirect measurements will not give exact results.

A Summary of IAQ studies is shown in table 1.

Table 1. Summary of IAQ Studies

Title	Author	Remarks
Characterizing the Range of Children's Pollutant Exposure during School Bus Commutes	Lisa D. Sabin, Eduardo Behrentz, Arthur M. Winer, Seong Jeong, Dennis R. Fitz, David V. Pankratz, Steven Colome, and Scott A. Fruin.	The paper shows the scope of exposure inside the bus depend on various factors, including window position, exhaust self-pollution, bus type and route type.
Field Assessment of Enclosed Cab Filtration System Performance Using Particle Counting Measurements	John A. Organiscak, Andrew B. Cecala & James D. Noll.	Authors use a specific particle counting method and show that out of four cabs, three cabs accomplished protection factor higher than 1,000 in limestone mines field.
Reducing Enclosed Cab Drill Operator's Respirable Dust Exposure with Effective Filtration and Pressurization Techniques	Andrew B. Cecala, John A. Organiscak, Jeanne A. Zimmer, William A. Heitbrink, Ernest S. Moyer, Michael Schmitz, Eugene Ahrenholtz, Chris C. Coppock & Earle H. Andrews	Some modifications were applied in the drill's filtration and pressurization system to improve cab efficiency to 93.4% in the mining industry.
Test for the Integrity of Environmental Tractor Cab Filtration Systems	Ernest S. Moyer, William A. Heitbrink & Paul A. Jensen	A low-cost, optical particle counter was applied to assess how tractor cab filtration systems perform. Leak sites were identified and sealed.
Exposure Assessment of Heavy-Equipment Operators to Diesel Particulate Matter	Hansen, D.S.	The exposure assessment of heavy-equipment operators to CO, NO2, and DPM was conducted to establish a correlation coefficient for the diesel gases and particulate matter and baseline exposure measurements for heavy equipment operators to emissions as represented by NIOSH method 5040

2.1.2 Equipment Emissions Studies

Plenty of studies were done about emissions of heavy duty diesel equipment in construction. The most relevant ones to our study can be categorized into these groups: 1- Estimating fuel use and emission rates with Simple and Multiple Linear Regression and Artificial Neural Network Models-2- Assessing effects of idling and operational efficiency and engine variable impact on fuel use and emission rates-3- Estimating emission inventories-4- Developing methodologies for data collection. A summary of equipment emissions studies is shown in Table 2.

Table 1. Summary of Equipment Emissions

Title	Author	Remarks
Development of Productivity-based Estimating Tool for Energy and Air Emissions from Earthwork Construction Activities	Hajji, A. and Lewis, P.	The paper develops a framework of a model to estimate the production rate, activity duration, fuel use, and pollutant emissions in earthworks activities.
Toward an Integrated Framework for Estimating, Benchmarking, and Monitoring the Pollutant Emissions of Construction Operations.	Ahn, C., Lewis, P., Golparvar-Fard, M. and Lee, S.)	It establishes a framework model that could be a systematic and generic reference to manage construction operations emissions.
Effects of Engine Idling on NAAQS Criteria Pollutant Emissions from Nonroad Diesel Construction Equipment	Lewis, P., Rasdorf, W., Frey, H.C., Leming, M.	The paper introduces a methodology to quantify the impact of idling on National Ambient Air Quality Standards criteria pollutant emissions (NO_x, CO, HC, PM)
Evaluation of On-Site Fuel Use and Emissions over the Duration of a Commercial Building Project	Rasdorf, W., Lewis, P., Marshall, S. K., Arocho, I., and Frey, H.C.	They established a temporal relationship between emissions and fuel use of construction activities with a project schedule. It is shown that site construction activities generate heaviest pollutants.

Title	Author	Remarks
A Methodology for Estimating Emissions Inventories for Commercial Building Projects	Marshall, S. K., Rasdorf, W., Lewis, P., and Frey, H.C.	It introduces a methodology to show a direct link between building construction activities and emissions. It can determine fuel use and emission at any stage of the construction process.
Impact of Idling on Fuel Use and CO2 Emissions of Nonroad Diesel Construction Equipment	Lewis, P., Leming, M., and Rasdorf, W.	It introduces a methodology to evaluate how idling can affect fuel use and carbon dioxide (CO2) emissions of diesel construction equipment. It used mathematical models to predict emissions.
Assessing the Effects of Operational Efficiency on Pollutant Emissions of Nonroad Diesel Construction Equipment	Lewis, P., Leming, M., Frey, H.C., and Rasdorf, W.	The authors present a methodology to evaluate how equipment operational efficiency can affect pollutant emissions from construction equipment in construction sites. This methodology can estimate how many more percentage of pollutions emitted as a result of operational efficiency reduction.
Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment	Frey, H. C., Rasdorf, W., and Lewis, P.	This paper summarizes field research results from a portable emissions monitoring system. It collected fuel use and emissions data from 39 different type of equipment to evaluate how engine attribute has an influence on them.
Field Procedures for Real-World Measurements of Emissions from Diesel Construction Vehicles	Rasdorf, W., Frey, H.C., Lewis, P., Kim, K., Pang, S-H., and Abolhassani, S.	This paper outlines field data collection standard procedures for construction equipment. It developed a study design, instrumentation installation and use, and measurements of the field.
Requirements and Incentives for Reducing Construction Vehicle Emissions and Comparison of Non-road Diesel Engine Emissions Sources	Lewis, P., Rasdorf, W., Frey, H.C., Pang, S-H., and Kim, K.	This paper presents the challenges to quantify emissions from non-road construction equipment. It explains related governmental rules and stimuli to reduce emissions. It introduces the need to collect additional data, and determine and compare different sources for emissions data.
Development and Use of Emissions Inventories for Construction Vehicles	Lewis, P., Frey, H.C., and Rasdorf, W.	It represents a methodology to inventory construction fleet emissions using a portable emissions measurement system (PEMS) to collect real-world data.
Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators	Abolhasani S., Frey, H.C., Kim, K., Rasdorf, W., Lewis, P., Pang, S-H.	The authors develop a study design to utilize a portable emission measurement system (PEMS) for excavators.

Title	Author	Remarks
Comparison of Real World Emissions of Backhoes, Front-End Loaders, and Motor Graders for B20 Biodiesel vs. Petroleum Diesel and for Selected Engine Tiers	Frey, H.C., Rasdorf, W., Kim, K., Pang, S-H., and Lewis, P.	The authors deployed portable emission measurement system (PEMS) to measure fuel consumption and emission rates. Also, they developed a methodology for study design, collecting field data, data screening and quality assurance, data analysis, and data benchmarking.
Characterization of Real-World Activity, Fuel Use, and Emissions for Selected Motor Graders Fueled with Petroleum Diesel and B20 Biodiesel	Frey, H.C., Kim, K., Rasdorf, W., Pang, S-H., and Lewis, P.	The authors utilized PEM to measure fuel use and emissions of six selected motor graders. They developed an empirical modal-based model for equipment fuel use and emissions to compare duty cycles, motor graders, and fuels.
Benchmarking Fuel Use and Emission Rates for Heavy Duty Diesel Highway Maintenance Equipment	Lewis, P., Fitriani, H., and Shan, Y.	The paper introduces a dataset of real world fuel use and emissions rates that are categorized by pollutant type, equipment type, EPA Engine Tier standards, and fuel type (petroleum diesel and B20 biodiesel).
Engine Variable Impact Analysis of Fuel Use and Emissions for Heavy Duty Diesel Maintenance Equipment	Lewis, P., Fitriani, H., and Arocho, I.	This paper used multiple linear regression models to investigate the relationships between engine activity variables and fuel use and emissions rates. The results show that manifold absolute pressure had the highest correlation. Therefore, estimating models were developed to estimate fuel use and emission rates based on manifold absolute pressure.
Characterizing Fuel Use and Emissions Rates of Heavy-Duty Diesel Equipment: A Case Study for Wheel Loaders	Fitriani, H. and Lewis, P.	This paper analyzed an engine load modal to test five wheel loaders and estimating the weighted-average fuel use and emissions rates. It used Monte Carlo simulation to model the distributions of the weighted-average fuel use rate for each wheel loader.
Comparison of Simple Linear Regression and Multiple Linear Regressions for Estimating Fuel Use and Emission Rates for Excavators	Fitriani, H. and Lewis, P.	The authors used PEMS to collect fuel use and emission rates data along with engine performance data for three excavators. They used simple linear regression (SLR) and multiple linear regression (MLR) to develop predictive models. They concluded that the values of coefficient of determination (R^2) for each model determined that MLR accounted for the higher percentage of variability in the data compared to SLR.
Results of a Case Study on Quantifying Fuel Use and Emissions for a Bridge Replacement Project	Hazzard, E. and Lewis, P.	The authors conducted a case study was done on a bridge replacement project by Oklahoma Department of Transportation (ODOT) to

Title	Author	Remarks
		develop a baseline for actual-world activity, equipment, fuel use, and emissions data.
Comparison of Predictive Modeling Methodologies for Estimating Fuel Use and Emission Rates for Wheel Loaders	Fitriani, H. and Lewis, P.	The paper used real-world data from five wheel loaders to represent three predictive modeling methodologies for fuel use and emission rates estimation. Three predictive models are simple linear regression, multiple linear regression, and artificial neural network which ANN has the highest percentage of variability based on the coefficient of determination (R^2).
Case Study of an Energy and Environmental Inventory for a Municipal Heavy-Duty Diesel Equipment Fleet	Lewis, P., and Hajji	This paper demonstrates a practice-ready methodology to develop an energy (diesel fuel) and environmental (pollutant emission) inventory for non-road HDD equipment. Fuel use and emissions calculation was based on an equation from Environmental Protection Agency NONROAD model.
Using Earned Value Management to Quantify Economic, Energy, and Environmental Sustainability in Construction Activities	Lewis, P. and Hazzard, E.	The paper proposed a plan-do-check-act approach of EVM to project managers to help them see the effectiveness of their decision. EVM also introduces a framework to show the relationships between fuel use, equipment cost, and air pollution as three crucial aspects of sustainable construction.
Comparison of Two Models for Estimating Equipment Productivity for a Sustainability Quantification Tool	Lewis, P., and Hajji	Data was collected from the Caterpillar Performance Handbook and RS Means Heavy Construction Cost Data. Then, They develop two models to estimate bulldozer productivity during excavation using multiple linear regression (MLR). They concluded that blade capacity, engine size, material type, operational efficiency, dozing distance, and operator skill level have the highest effects on the equipment productivity.
Estimating the Economic, Energy, and Environmental Impact of Earthwork Activities	Lewis, P. and Hajji, A	This paper represents a model framework in order to estimate production rate, unit cost, activity duration, activity cost, fuel use, and total CO2 emissions estimation during earthwork activities. The authors did a case study of a bulldozer performing a bulk excavation activity and did sensitivity analysis too.

Title	Author	Remarks
Evaluation of Construction Equipment Fleets through Fuel Use and Emissions Inventories	Lewis, P. and Hajji, A.	This paper evaluates the current status of the non-road diesel construction equipment fleet in Stillwater, Oklahoma and develops and analyzes a fuel use and emissions inventory. Equipment attributes like equipment type, engine size, engine age, pollutant regulations, fuel use, equipment usage, and carbon dioxide (CO_2) emissions were evaluated by the inventory.
Development and Use of Emissions Inventories for Construction Vehicles	Lewis, P., Frey, H.C., and Rasdorf, W.	This paper develops a methodology using a portable emissions measurement system (PEMS) for inventorying construction fleet emissions.
Methodology for Activity, Fuel Use, and Emissions Data Collection and Analysis for Non-road Construction Equipment	Frey, H. C., Rasdorf, W., Pang, S. H., Kim, K., Abolhasani, S., and Lewis, P.	It measures real-world duty cycles for specific types of non-road construction vehicles and characterizes in-use emissions and energy use of them.
Methods for Measurement and Analysis of In-Use Emissions of Non-road Construction Equipment	Frey, H.C., Rasdorf, W., Pang, S., Kim, K., and Lewis, P.	This paper develops data collection and analysis procedures for non-road construction vehicles. Field data collection procedure including study design development, PEMS installation, field measurements, data quality assurance, and analysis of the data.
Assessing the Economic, Energy, and Environmental Impacts of a Bridge Replacement Project	Hazzard, E. and Lewis, P.	It represents a case study which is a bridge replacement project done by the Oklahoma Department of Transportation (ODOT) to develop a baseline estimate for equipment activity, emission data, and fuel use.
Characterizing Equipment Cost, Fuel Use, and Emissions for Earthwork Activities	Lewis, P., Shan, Y., Hajji, A., and Hazzard, E.	This paper examines the relationship between construction fuel use, equipment costs, and air pollutant emissions in order to make more wise decision in construction planning and have more sustainability in construction.
Estimating Fuel Use and Emission Rates of Non-road Diesel Construction Equipment Performing Representative Duty Cycles	Lewis, P.	This dissertation establishes a methodology to improve fuel -road diesel construction equipment used in construction activities.

2.2. Assess the Energy, Economical, and Environment Impacts of Alternative Fuels

Biofuels are known as environmentally friendly products for years and some research has been done to promote using biofuels instead of petroleum products.

Su, Zhang, and Su (2015) recommended using biofuels to decrease greenhouse gas (GHG) emission. Water vapor, carbon dioxide, methane, nitrous oxide, and ozone are the greenhouse gases. They justified biofuels as low-carbon and sustainable energy for transportation equipment. They believe it is a way to follow The United Nations Framework Convention on Climate Change (UNFCCC) to keep global temperature rise to below 2° C in 2012.

Hill, Nelson, Tilman, Polasky, and Tiffany (2006) introduced biofuels as a viable alternative to fossil fuels. They investigated environmental and economic benefits of biofuels from soybeans through life-cycle accounting and showed that compare to fossil fuels, it emits 41% less greenhouse gas. They claimed that biofuels reduce many pollutants like nitrogen, phosphorus, and pesticide release.

Strogen and Horvath (2013) investigated GHG emissions from four generalized stages of U.S. petroleum and biofuels: component operation, fuel production, equipment and vehicle manufacturing and maintenance, and infrastructure construction and maintenance. They concluded that capital-expenses and emissions for ethanol system are higher than the petroleum system. They justified it as a result of less equipment usage, feedstock diffuse nature, and feedstock and fuel low energy density.

Gallivan, Ang-Olson, Papson, and Venner (2010) conducted the National Cooperative Highway Research Program (NCHRP) Project 25-25 for American Association of State Highway and Transportation Officials (AASHTO) and provided a report that shows biofuels can reduce CO_2 emissions in construction compared to diesel.

2.3. Assess the Energy and Environmental Impact of Engine Tier Standards (Tier 0 vs. Tier 1 vs. Tier2)

It is a common belief that engines meeting emissions standards like tier standards can provide many benefits toward clean air. The need for research on the energy and environmental impact of engine tier standards arises when we can hardly find a study related to engine tier standards.

Fitriani and Lewis (2016) Quantified emissions rates of NO_x based on equipment and engine tier types for diesel construction equipment. Frey, Rasdorf, and Lewis (2010) analyzed approximately 119 hours of field data for petroleum diesel and 48 hours for B20 biodiesel. They collected engine attribute data such as horsepower, displacement, model year, engine tier, and engine load in order to assess how these factors affect fuel use rates and emission rates of hydrocarbons, nitrogen oxides, carbon dioxide, carbon monoxide, and opacity. They concluded that there is a strong positive relationship between petroleum diesel and B20 biodiesel fuel use, emission rates and engine displacement, horsepower, and load. Fuel and emission rates showed an inverse proportion to model year and engine tier. They emphasized that further investigation is required.

This dissertation addresses the gap in the literature to characterize activity patterns of heavy duty diesel construction equipment and determine how effective are emissions reduction methods including alternative fuels and engine standard technology regarding emission rates and fuel use in construction equipment.

CHAPTER III

METHODOLOGY AND RESULTS

This chapter provides all techniques and methods conducted in this research including assessing potential impacts of diesel exhaust on operator; assessing the energy, economic, and environment impacts of alternative fuels in off-road maintenance equipment; and assessing the energy and environmental impact of engine tier standards (tier 0 vs. tier 1 vs. tier2) in off-road maintenance equipment.

3.1. Assess Potential Impacts of Diesel Exhaust on Operator

This objective characterizes the impacts of tailpipe diesel exhaust emissions on IAQ in heavy equipment cabs. The working hypothesis for this objective was tailpipe pollutant concentrations of NO_x, CO, CO_2, and PM exceed industry PELs. The first objective was to compare tailpipe pollutant concentrations of these pollutants to their most appropriate NIOSH PEL. The second objective was to propose an approach to more fully characterize the impacts of diesel-related pollutants on IAQ in heavy equipment cabs. Outcomes of the case study will help determine whether or not additional study is merited and what the focus of those studies should be.

Tailpipe pollutant emissions data for NO_x, CO, CO_2, and PM were collected from five wheel loaders that were operating under real-world conditions. The wheel loaders ranged in model year from 2002 to 2005 and in horsepower rating from 126 hp to 149 hp. The EPA engine emissions technology type was either Tier 1 or Tier 2 for each wheel loader.

Limitations of this objective were related to the pollutants themselves. For example, the tailpipe emissions data that were collected from the wheel loaders included NO_x and PM; however, there are no specific OSHA PELs for NO_x and PM. There are OSHA PELs for NO_2 (which is included in NO_x) and Total Dust (which includes diesel-related PM); hence, there were no direct comparisons between the field data and the exposure limit for these two pollutants. For CO and CO_2, however, direct comparisons were possible.

3.1.1. Methodology

Although there is little data directly related to IAQ in heavy equipment cabs, an argument may be made for potential harmful health impacts to equipment operators based on their close relationship to high concentrations of diesel pollutants from the tailpipe; therefore, tailpipe pollutant concentrations of NO_x, CO, CO_2, and PM were characterized for five wheel loaders. The analysis was based on real-world data collected from in-use wheel loaders.

The central component of the emissions data collection effort was a portable emissions measurement system (PEMS). The PEMS was placed onboard each wheel loader and sample probes drew exhaust samples from the tailpipe. The PEMS collected and recorded second-by-second pollutant concentration data in parts per million (ppm) for NO_x, CO, and CO_2, and in milligrams per cubic meter (mg/m3) for PM. The PEMS gathered corresponding engine performance data including manifold absolute pressure (MAP), revolutions per minute (RPM), and intake air temperature (IAT); however, an engine activity analysis was not conducted as part of this analysis. Other equipment data were collected including engine rated horsepower, engine displacement, equipment model year, and EPA engine tier.

A minimum of one hour of data was targeted for collection from each wheel loader. The field data underwent a thorough quality assurance process in order to identify missing or invalid values. The purpose of the quality assurance process was to ensure the availability of a robust dataset for statistical analysis. Analysis of the data included plotting the concentration of each pollutant versus time in order to observe the time series relationships. The data were characterized by determining the minimum, maximum, and average values for the concentrations of each pollutant. Furthermore, the 8-Hour Time Weighted Average for each pollutant was calculated using the following formula:

8-HR. TWA P_i = (Average P_i x Total T_i)/(8 hours)

Where 8-HR. TWA = 8-hour Time Weighted Average for pollutant i (ppm or mg/m3); Average P_i = Average concentration of pollutant i (ppm or mg/m^3); and Total T_i = Total time of exposure to pollutant i (hours). The 8-HR TWA is used as for relative comparison to the OSHA PEL for each pollutant; however, the average concentration may be of more importance since it is the expected value the operator would be exposed to regardless of the total time of exposure.

3.1.2. Results

Table 1 summarizes the key attributes for the five wheel loaders included in the case study. The equipment ranged from 126 hp to 149 hp with an average of 134 hp. Each wheel loader had an engine displacement of approximately six liters. The model years ranged from 2002 to 2005 and each wheel loader had EPA engine tier technology of Tier 1 or Tier 2. The total amount of data, referred to as exposure time (T_i) for the case study, ranged from a minimum of about one hour (WL 3) to over five hours (WL 2). The average exposure time was about three hours.

Table 2. Summary of Wheel Loader Attributes

Equipment	**Horsepower (HP)**	**Displacement (L)**	**Model Year**	**Engine Tier**	**Time, T_i (Hours)**
Wheel Loader 1 (WL 1)	149	5.9	2004	2	4.23
Wheel Loader 2 (WL 2)	130	5.9	2002	1	5.30
Wheel Loader 3 (WL 3)	130	5.9	2002	1	0.95
Wheel Loader 4 (WL 4)	126	5.9	2002	1	1.87
Wheel Loader 5 (WL 5)	133	6.0	2005	2	3.29

Figure 2 through Figure 5 show the time series data for NO_x, CO, CO_2, and PM, respectively, for Wheel Loader 1. Figure 6 and Figure 7 show the time series data for RPM and MAP, respectively. Similar graphs were developed for Wheel Loader 2 through Wheel Loader 5, but the results for Wheel Loader 1 only are shown here for brevity. The remaining results for Wheel Loader 2 through Wheel Loader 5 are shown in the appendix A. These graphs show the minimum and maximum values as well as trends over the span of time that the data were collected. A cursory inspection of the figures reveals that all six graphs have a similar shape. For example, high concentrations of pollutant correspond with high levels of RPM and MAP during the same timeframe. Likewise, low concentrations of pollutant correspond with low levels of RPM and MAP during the same timeframe. Similar results were observed for Wheel Loader 2 through Wheel Loader 5. This is an indication that pollutant concentrations may be positively correlated with engine activity; that is, as RPM and MAP increase, so do pollutant concentration levels of NO_x, CO, CO_2, and PM.

Table 4 summarizes the diesel-related pollutant concentrations for Wheel Loader 1 through Wheel Loader 5. For NO_x, the overall average concentration of 360 ppm was 72 times greater than the PEL of 5 ppm. The 8-HR TWA of 210 ppm was 42 times greater than the PEL. The overall maximum value of 1,100 ppm was 220 times greater than the PEL, although this value was not sustained for long periods of time. Furthermore, it must be made clear that the PEL is based on NO_2 and not total NO_x.

For CO, the overall average of 140 ppm was approximately three times greater than the PEL of 50 ppm. The 8-HR TWA of 84 ppm was slightly less than twice as high as the PEL. The overall maximum value of 3,400 ppm was 68 times greater than the PEL, although this value was not sustained for long periods of time.

For CO_2, the overall average of 31,000 ppm was over six times greater than the PEL of 5,000 ppm. The 8-HR TWA of 18,000 ppm was over three times greater than the PEL. The overall maximum value 89,000 ppm was nearly 18 times greater than the PEL.

For PM, the overall average of 7 mg/m^3 was about one-half the value of the PEL of 15 mg/m^3. The 8-HR TWA of 4.1 mg/m^3 was about one-fourth the value of the PEL. The overall maximum value of 56 mg/m^3 was nearly four times greater than the PEL. It must be made clear that the PEL is based on Total Dust, of which diesel particulate matter is a portion. The measurements for PM in this analysis represent diesel particulate matter only and do not include any other particle measurements; therefore, it is quite possible that the overall average and 8-HR TWA for Total Dust inside heavy equipment cabs may be exceeded.

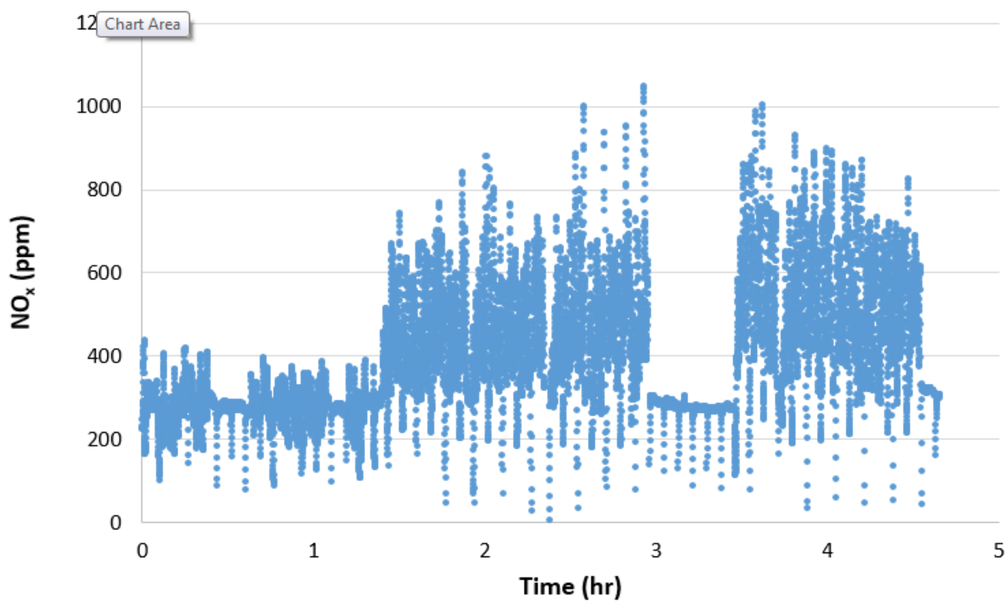


Figure 2. NO_x versus Time for WL1

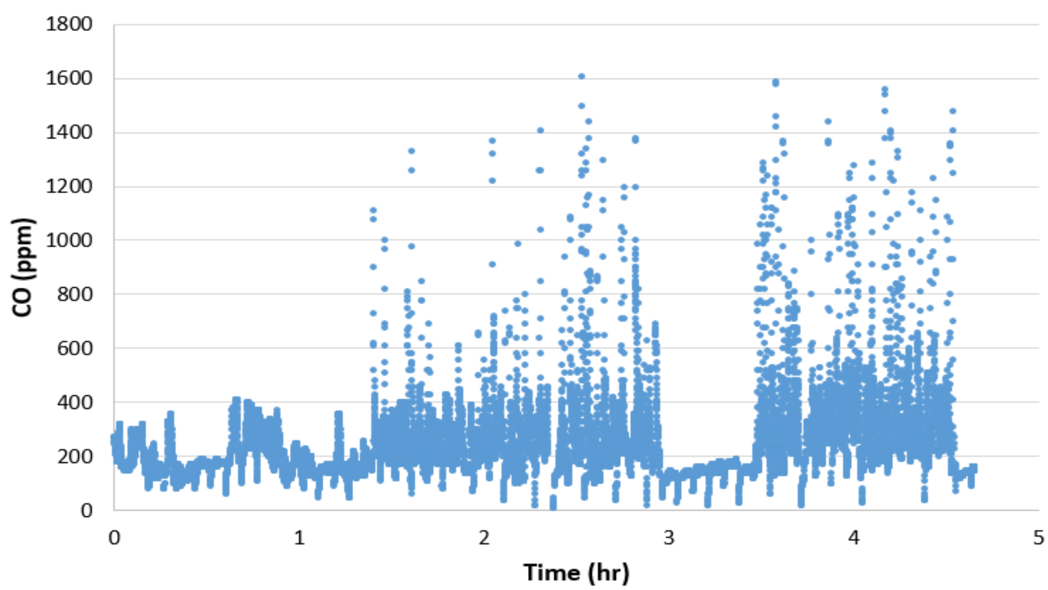


Figure 3. CO versus Time for WL1

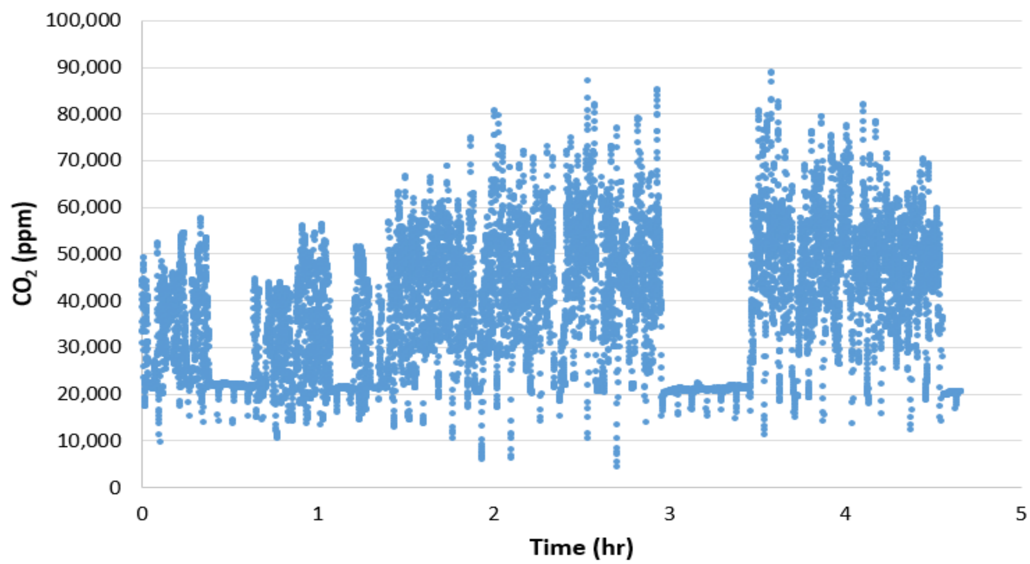


Figure 4. CO_2 versus Time for WL1

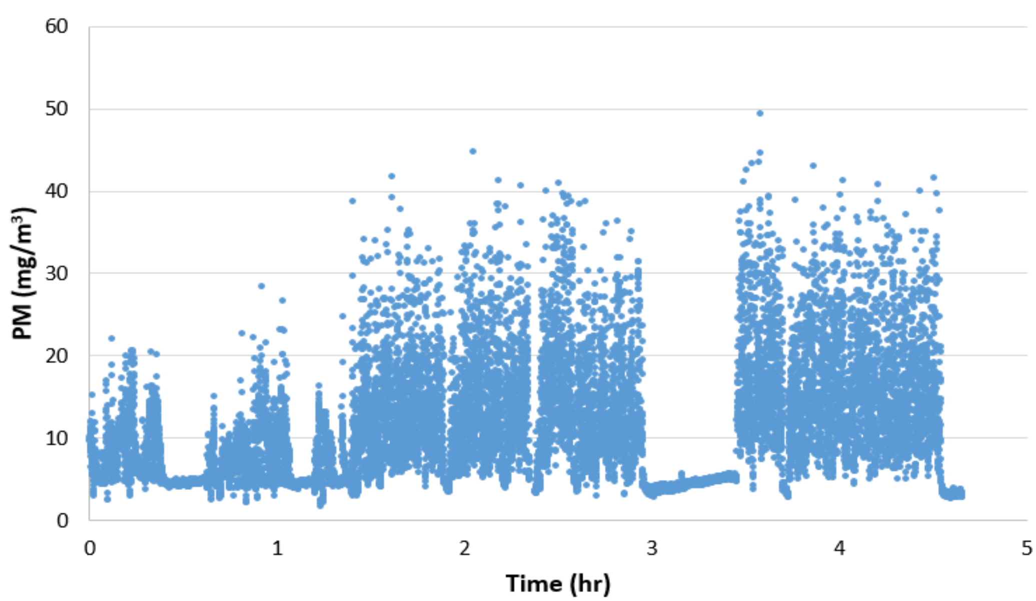


Figure 5. PM versus Time for WL1

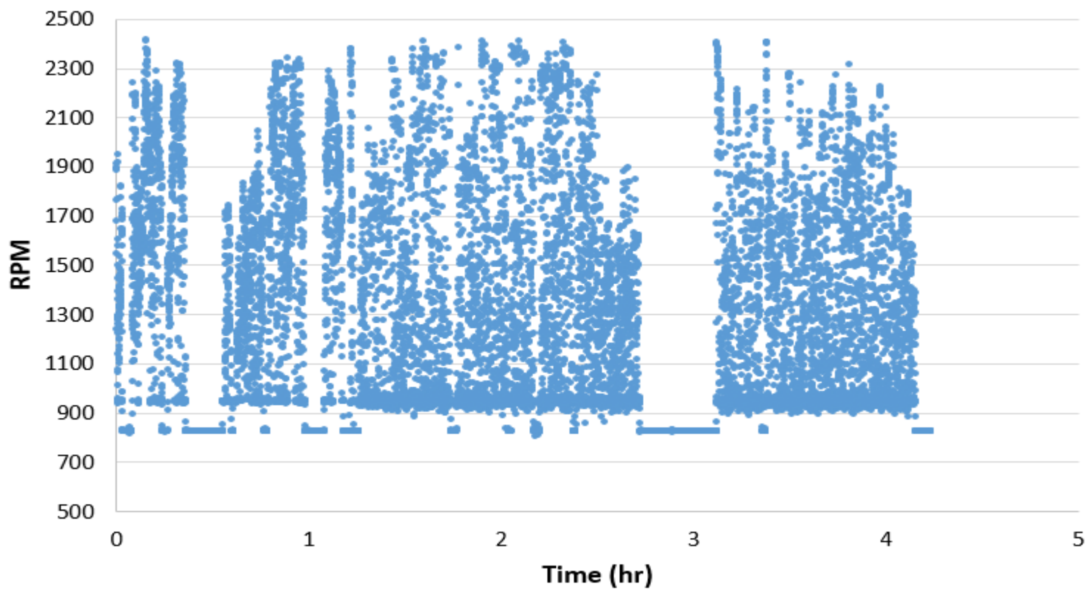


Figure 6. RPM versus Time for WL 1

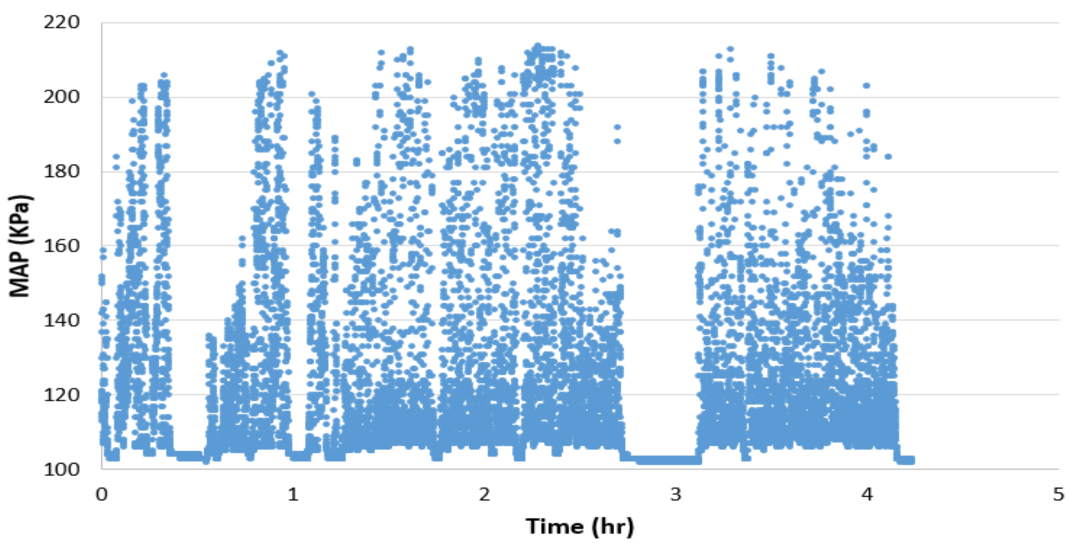


Figure 7. MAP versus Time for WL 1

Table 3. Summary of Diesel-Related Pollutant Concentrations

		NO_x (ppm) PEL = 5 ppm	CO (ppm) PEL = 50 ppm	CO_2 (ppm) PEL = 5,000 ppm	PM (mg/m^3) PEL = 15 mg/m^3
WL 1	Min	7.0	10	4,600	1.8
	Max	1,100	1,600	89,000	49
	Avg	400	260	38,000	11
	8-HR TWA	230	150	22,000	6.7
WL 2	Min	67	10	13,000	2.2
	Max	950	3,400	76,000	56
	Avg	440	170	36,000	9.7
	8-HR TWA	260	100	21,000	5.6
WL 3	Min	15	0.0	100	0.7
	Max	670	270	52,000	11
	Avg	330	98	21,000	2.5
	8-HR TWA	190	57	12,000	1.5
WL 4	Min	120	0.0	3,100	0.8
	Max	660	670	13,000	24
	Avg	340	47	32,000	6.7
	8-HR TWA	200	27	19,000	3.9
WL 5	Min	83	10	14,000	2.4
	Max	1,000	1,300	81,000	31
	Avg	280	150	28,000	4.8
	8-HR TWA	160	85	16,000	2.8
Overall	Min	7.0	0.0	100	0.7
	Max	1,100	3,400	89,000	56
	Avg	360	140	31,000	7.0
	8-HR TWA	210	84	18,000	4.1

3.2. Assess the Energy, Economical, and Environment Impacts of Alternative Fuels

Advocates for biodiesel claim that it is a clean, renewable, and cost-effective fuel that provides economic and environmental benefits while easing the energy impacts of petroleum diesel. However, many of the claims presented in the popular press are often anecdotal in nature and frequently are not based on empirical data. The purpose of this objective is to present the results of a case study that comparatively analyzes the economic, energy, and environmental impacts of biodiesel versus petroleum diesel in off-road maintenance equipment.

3.2.1. Methodology

Using the same real world data for objective 1, statistical comparisons of B20 versus petroleum diesel fuel use were performed on a fleet of backhoes, motor graders, and wheel loaders. Hypothesis testing was used to determine whether or not there was a statistically significant difference between B20 and petroleum diesel in fuel prices, fuel use rates, and emissions rates. Scatterplots of B20 versus petroleum diesel were developed for fuel prices, fuel use rates, and emissions rates to show how the two fuels are related to each other.

Although numerous case studies exist extolling the benefits of biodiesel fuel use in on-road vehicles ("America's Largest Home Runs on Biodiesel in North Carolina",…), few could be found that focused on off-road equipment (“Biodiesel Clears the Air in Underground Mines”2009; Frey, Rasdorf, Kim, Pang, & Lewis2008). The primary objective of this objective was to compare the economic, energy, and environmental impacts of B20 biodiesel versus petroleum diesel fuel use in off-road maintenance equipment. Economic impacts were compared based on national average retail fuel prices per gas gallon equivalent. Energy impacts were compared based on real-world fuel consumption rates (gallons per hour) of in-use maintenance equipment. Environmental impacts were compared based on real world emissions rates (grams per gallon) of NO_x, HC, CO, CO_2, and PM. Comparisons for fuel consumption rates and emissions rates were not adjusted based on the heating value of the two fuels; thus, a direct gallon-for-gallon comparison was performed for B20 versus petroleum diesel.

Comparisons of B20 versus petroleum diesel were statistical in nature to provide empirical insight into the economic, energy, and environmental impacts of the two fuels. Hypothesis testing was performed to determine whether or not there was a statistically significant difference in fuel prices, fuel use rates, and emissions rates between B20 and petroleum diesel. Scatterplots of B20 versus petroleum diesel were developed for fuel prices, fuel use rates, and emissions rates in order to show how characteristics of the two fuels are directly related to each other. These graphs also were helpful in determining the relationship between B20 and petroleum diesel by evaluating the Pearson correlation coefficient r and the goodness-of-fit of the trend lines R^2.

3.2.2. Results

3.2.2.1. Economic Impacts

For the purposes of this objective, economic impacts were assessed by comparing the national average retail prices of petroleum diesel and B20 biodiesel. Data for the two fuels were collected from the United States Department of Energy Clean Cities Alternative Fuel Price Report for April 2017 ("Clean Cities Alternative Fuel Price Report",2017). Figure 8 represents the average retail price, in gas gallon equivalent (GGE), of petroleum diesel and B20 for the period from April 2000 to April 2017. During this period, the national average retail price of the two fuels trended in a similar manner, with B20 typically being a few cents higher than petroleum diesel. The overall national average fuel price per GGE for petroleum diesel and B20 during this period was \$2.55 and \$2.73, respectively; hence, the national average fuel price of B20 was approximately 7% higher than petroleum diesel.

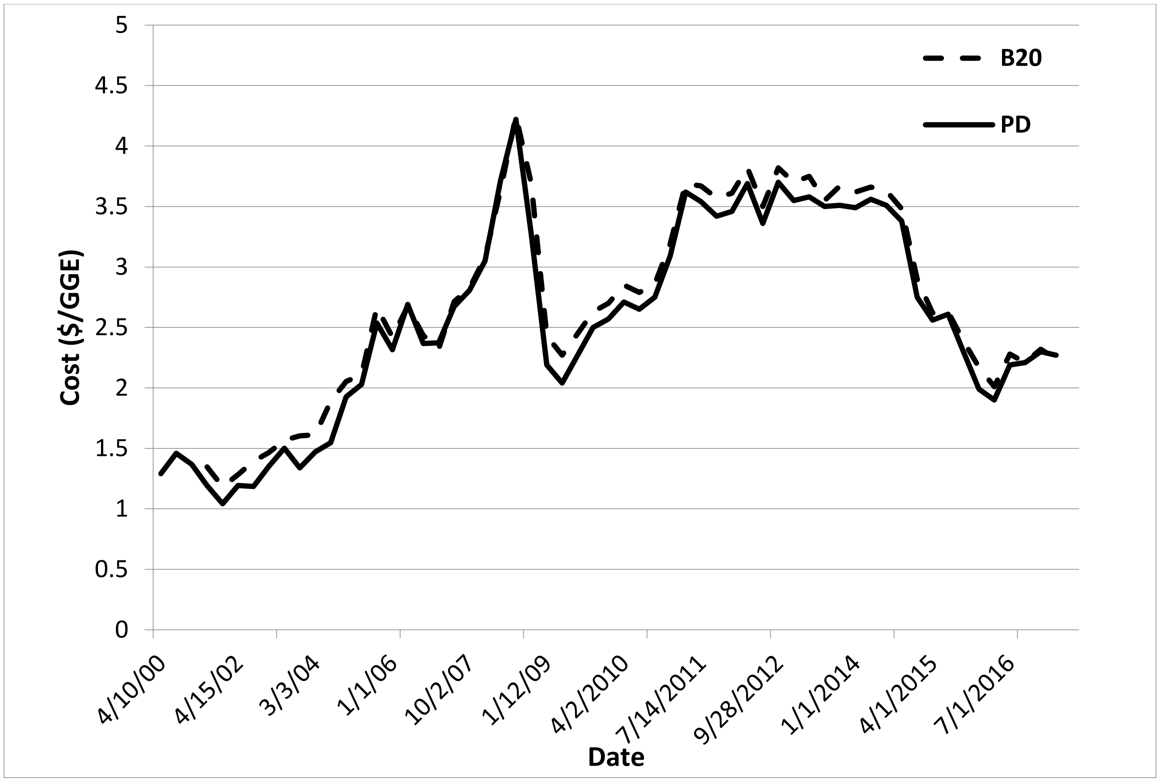


Figure 8. Average US Retail Prices of Petroleum Diesel and B20 versus Time

Figure 9 presents another comparison of the average US retail price of B20 versus petroleum diesel. Here it is clear to see that B20 almost always had a higher average retail price than petroleum diesel, with an average difference of about $0.11 per GGE. A trend line was added to the data to determine the relationship between B20 and petroleum diesel fuel prices. The resulting equation of the line accounted for nearly all of the variability in the data ($R^2 = 0.99$). Although it is impossible to predict future fuel prices, the equation $B20 = 0.98\ PD + 0.16$ provides a useful tool to estimate the price per GGE of B20 when the price of petroleum diesel is known.

Based on Figures 8 and 9, it is reasonable to assume that the economic impact of B20 biodiesel is higher than that of petroleum diesel because it costs more.

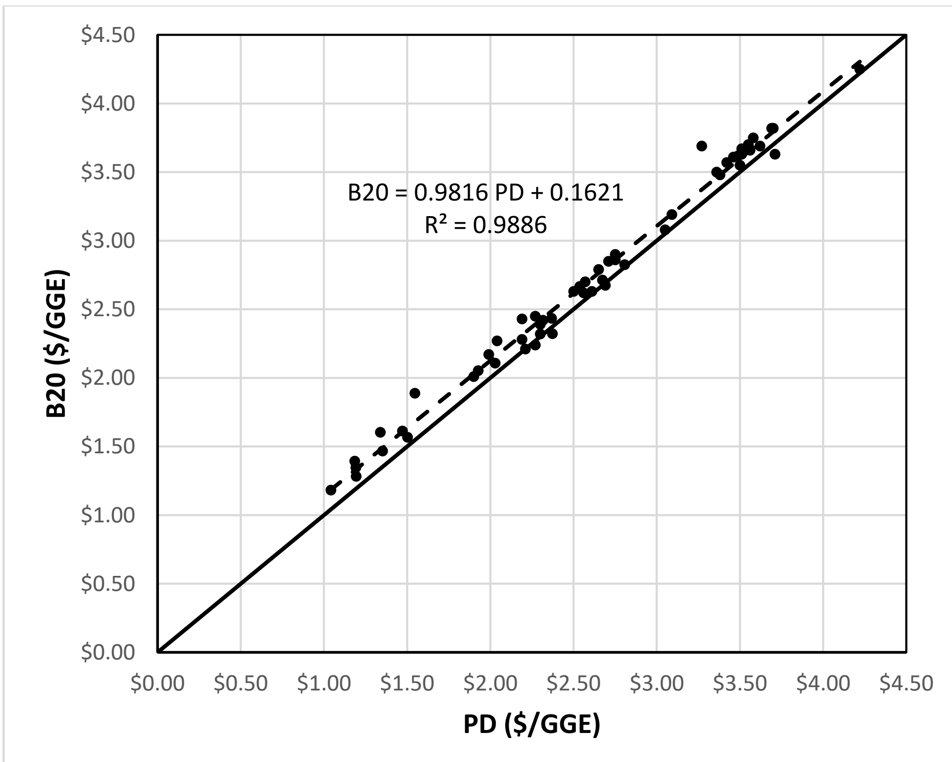


Figure 9. Average US Retail Price of B20 versus Petroleum Diesel

3.2.2.1.1. Discussion

With regard to economic impacts, the average price of B20 was approximately seven percent higher than that of petroleum diesel based on 16 years of data; however, there was not enough evidence to conclude that this difference in average price was statistically significant. Although there was no statistically significant difference in the average fuel prices of B20 and petroleum diesel, the evidence showed that the price of B20 trended higher than petroleum diesel by an average of $0.11 per gas gallon equivalent over the last 16 years. Thus, it is not likely that maintenance equipment fleet managers would choose to use B20 over petroleum diesel based on price alone.

3.2.2.2. Energy Impacts

For the purposes of this objective, energy impacts were evaluated based on hourly fuel use in terms of gallons per hour (gal/h). This evaluation was based on the same dataset that was assembled by researchers at North Carolina State University (Frey, Rasdorf, & Lewis, 2010; Rasdorf, Frey, Lewis, Kim, Pang, & Abolhassani, 2010; Frey, Rasdorf, Pang, Kim, Abolhasani, & Lewis, 2007; Frey, Rasdorf, Pang, Kim, & Lewis, 2007). The dataset provided real-world fuel use and engine load data that was collected from in-use equipment on actual job sites through the use of a portable emissions measurement system (PEMS).

Of particular interest for the energy analysis, the dataset included mass per time fuel use rates and corresponding engine loads for five backhoes (BH), six motor graders (MG), and four wheel loaders (WL). Each item of equipment was fueled once with petroleum diesel and monitored, and then fueled a second time with B20 biodiesel and monitored; thus, a direct comparison of fuel use rates of B20 versus petroleum diesel for all 15 items of equipment was possible.

Table 5 summarizes average engine loads and fuel use rates for petroleum diesel and B20 for all 15 items of equipment. Manifold absolute pressure (MAP) measured in kilopascals (KPa) was used as a surrogate for engine load since there is a positive correlation between MAP and fuel use rates (Lewis, Fitriani, & Arocho,2015). Fuel use rates for B20 and petroleum diesel were not adjusted to account for differences in heating values between the two fuels; thus, a straight comparison of field measured fuel use rates is presented. For each item of equipment, a 2-Sample t-test was conducted to compare the average fuel use rates of B20 and petroleum diesel. For all items of equipment, except MG 2, there was a statistically significant difference at the 0.05 level between the average fuel use rates of B20 and petroleum diesel.

For Backhoes, B20 had about 1% higher average fuel use rates than petroleum diesel even though average engine loads for each fuel were the same. For Motor Graders, however, B20 had 2% higher average fuel use rates than petroleum diesel in spite of having 6% lower average engine loads. For Wheel Loaders, B20 had 30% higher average fuel use rates than petroleum diesel even though average engine loads were less than 2% higher. For all 15 items of equipment, B20 had 6.7% higher overall average fuel use rates than petroleum diesel, even though overall average engine loads were 1.6% lower.

Table 4. Summary of Average Engine Load (MAP) and Fuel Use

		MAP (KPa)		Fuel Use (gal/h)		
Item	**EPA Tier**	**PD**	**B20**	**PD**	**B20**	**% Diff**
BH 1	2	112	115	0.5	0.6	33%
BH 2	0	105	108	1.4	1.7	21%
BH 3	1	114	107	1.7	1.0	-44%
BH 4	1	101	104	0.8	1.2	47%
BH 5	2	111	108	0.5	0.4	-7%
Average		*108*	*108*	*0.97*	*0.98*	*0.8%*
MG 1	1	174	169	5.5	5.1	-6%
MG 2	2	115	107	1.7	1.7	2%[1]
MG 3	1	149	137	2.5	3.8	48%
MG 4	0	113	103	2.9	1.3	-54%
MG 5	0	120	124	2.6	3.4	31%
MG 6	3	169	153	2.5	2.7	11%
Average		*140*	*132*	*2.95*	*3.02*	*2%*
WL 1	1	118	115	1.6	1.0	-37%
WL 2	1	119	119	0.9	1.2	24%
WL 3	1	126	125	1.2	2.2	85%
WL 4	2	105	117	0.8	1.5	89%
Average		*117*	*119*	*1.11*	*1.45*	30%
Overall Average		***123***	***121***	***1.8***	***1.9***	***6.7%***

[1] No statistically significant difference at the 0.05 level.

Figure 10 provides a graphical comparison of average fuel use rates for B20 versus petroleum diesel. According to Figure 10, nine items of equipment had a higher average fuel use rate for B20 and four items had a higher average fuel use rate for petroleum diesel; two items of equipment had approximately the same average fuel use rates for both fuels. There was also a strong positive correlation between the average fuel use rates of B20 and petroleum diesel (Pearson's r = 0.85). A trend line added to the data yielded an equation of $B20 = 0.86\ PD + 0.37$ ($R^2 = 0.72$). Although actual fuel use rates are difficult to predict, the equation provides a general estimate of a B20 fuel use rate for an item of equipment if its petroleum diesel fuel use rate is known. This information is helpful to fleet managers who may be considering using B20 as an alternative to petroleum diesel and would like to know an expected fuel use rate.

Figure 11 presents a comparison of B20 and petroleum diesel average fuel use rates as a function of average engine loads for all 15 items of equipment. This relationship was characterized by inserting trend lines in the data. At low engine loads (MAP = 100-110 KPa), which typically correspond to idling, there was virtually no difference in average fuel use rates for B20 and petroleum diesel. However, as engine loads increased, B20 fuel use rates increased 35% faster than petroleum diesel based on the slope components of the respective trend lines. For example, at MAP = 160 KPa, the average fuel use rate was approximately 1 gal/h higher for B20 than for petroleum diesel.

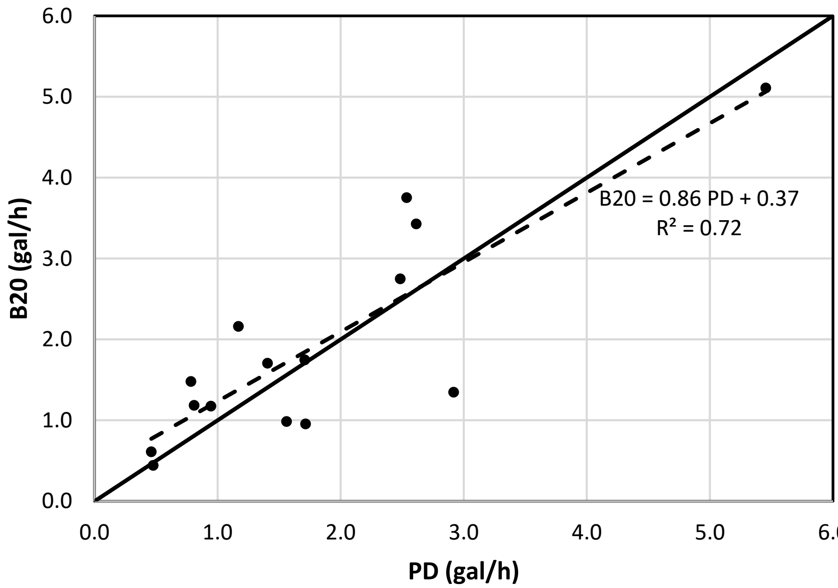


Figure 10. Fuel Use Rates of B20 versus Petroleum Diesel

Strong positive correlations existed between fuel use rates and engine loads for B20 and petroleum diesel, with R-values of 0.84 and 0.75, respectively. The trend lines for B20 and petroleum diesel also predicted fuel use rates based on MAP values reasonably well, with the line equations accounting for approximately 71% and 57% of the variability in the respective data. These equations provide useful tools for fleet managers to estimate fuel use rates based on average MAP-based engine loads for both types of fuel. Although petroleum diesel fuel use rates are frequently published in textbooks and equipment manufacturer handbooks, B20 fuel use rates are difficult to find (Nichols, and Day, 2005; "Caterpillar Performance Handbook",2014).

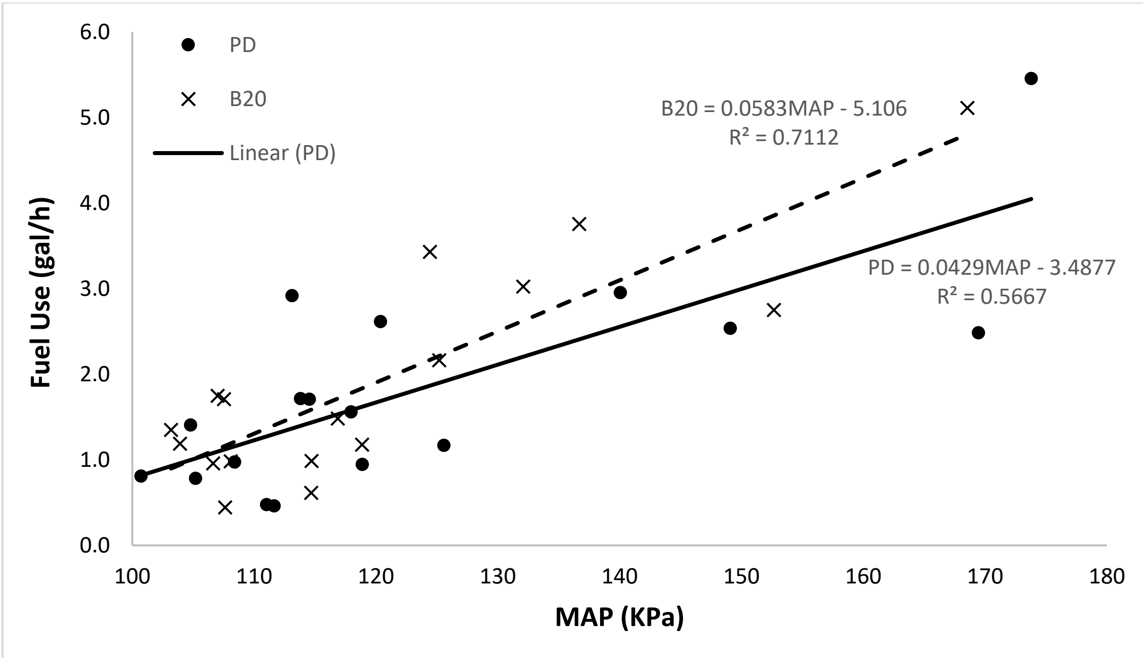


Figure 11. Fuel Use versus Engine Load (MAP) for Petroleum Diesel and B20

3.2.2.2.1. Discussion

Concerning energy impacts, there was enough evidence to conclude that equipment fueled with B20 had a higher average hourly fuel use rate than equipment fueled with petroleum diesel. There was a statistically significant difference between average hourly fuel use rates of B20 and petroleum diesel for 14 of the 15 items of equipment in the case study. There were only five items of equipment in which B20 had a lower average hourly fuel use rate than petroleum diesel. Overall, B20 had an approximately seven percent higher average hourly fuel use rate than petroleum diesel for the case study fleet.

Furthermore, B20 had higher fuel use rates at higher engine loads than petroleum diesel – as engine load increased, the difference between B20 and petroleum diesel average fuel use rates increased with B20 being higher. It is also noted that B20 has a lower heating value than petroleum diesel, which means that equipment must consume about 1.02 gallons of B20 to produce the same amount of work as 1.0 gallon of petroleum diesel ("Clean Cities Alternative Fuel Price Report",2017). Again, it is unlikely that maintenance equipment fleet managers would choose to use B20 over petroleum diesel based only on fuel consumption rates.

3.2.2.3. Environmental Impacts

Environmental impacts were characterized based on emissions rates of NO_x, HC, CO, CO_2, and PM. The same NC State dataset used for the energy analysis was used for the environmental analysis. Emissions rates for each pollutant from both B20 and petroleum diesel were compared for all 15 items of equipment. Emissions rates are presented on a gram per gallon basis and were not adjusted to account for differences in heating values of the fuels; thus, a direct comparison of pollutants emitted per gallon of fuel used for each fuel type is presented.

Table 6 provides a summary of average emissions rates of NO_x, HC, CO, CO_2, and PM for B20 and petroleum diesel, along with the percentage difference in the average emissions rates, for all 15 items of equipment. The total number of seconds (n) that each item of equipment was observed while using each fuel is provided. In order to determine if there was a statistically significant difference in the average emissions rates of each pollutant for each fuel type, a 2-Sample t-test was conducted for each pollutant on each item of equipment. In all but five cases (see footnote 1 in Table 6), the results of the tests indicated that there was a statistically significant difference in average emissions rates between the two fuels.

Table 5. Summary of Average Emissions Rates for Petroleum Diesel and B20

	n (sec)		**NO_x (g/gal)**			**HC (g/gal)**			**CO (g/gal)**			**CO_2 (g/gal)**			**PM (g/gal)**		
Item	**PD**	**B20**	**PD**	**B20**	**% Diff**	**PD**	**B20**	**% Diff**	**PD**	**B20**	**% Diff**	**PD**	**B20**	**% Diff**	**PD**	**B20**	**% Diff**
WL 1	19,064	8,070	132	151	14%	30	19	-37%	41	53	29%	9,912	9,698	-2%	0.9	1.8	100%
WL 2	3,403	15,143	179	170	-5%	14	27	93%	38	22	-42%	9,742	9,950	2%	0.6	0.6	2%[1]
WL 3	6,718	8,157	145	132	-9%	22	21	-5%	13	29	123%	9,977	9,736	-2%	1.0	0.7	-30%
WL 4	11,827	8,660	103	103	0%[1]	13	8	-38%	36	33	-8%	9,973	9,770	-2%	0.6	0.6	3%
Average	*10,253*	*10,008*	*140*	*139*	*-1%*	*20*	*19*	*-5%*	*32*	*34*	*7%*	*9,901*	*9,789*	*-1%*	*0.8*	*0.9*	*20%*
MG 1	16,293	20,606	129	129	0%[1]	16	15	-6%	17	22	29%	9,994	9,766	-2%	1.0	0.9	-10%
MG 2	10,767	11,999	148	172	16%	43	13	-70%	29	24	-17%	9,892	9,775	-1%	0.5	0.2	-60%
MG 3	5,590	9,614	131	122	-7%	77	18	-77%	20	22	10%	9,849	9,754	-1%	1.1	0.4	-64%
MG 4	10,040	12,138	215	131	-39%	43	32	-26%	72	313[2]	NA	9,821	9,256	-6%	0.7	0.8	4%[1]
MG 5	9,788	14,148	179	195	9%	15	24	60%	113	57	-50%	9,843	9,683	-2%	0.7	0.6	-14%
MG 6	7,757	7,130	86	100	16%	10	34	240%	7	12	71%	10,024	9,740	-3%	0.7	0.5	-29%
Average	*10,039*	*12,606*	*148*	*142*	*-4%*	*34*	*23*	*-33%*	*43*	*27*	*-36%*	*9,904*	*9,662*	*-2%*	*0.8*	*0.6*	*-29%*
BH 1	6,406	6,343	172	181	5%	14	56	300%	11	6	-44%	10,018	9,679	-3%	0.7	1.7	143%
BH 2	10,106	8,600	111	114	2%	15	14	-10%	80	66	-18%	9,906	9,902	0%[1]	1.1	1.1	-2%
BH 3	16,013	10,350	106	91	-14%	12	10	-13%	35	33	-5%	9,937	10,063	1%	1.1	1.1	0%[1]
BH 4	9,780	9,716	164	139	-15%	13	33	154%	61	73	20%	9,932	9,634	-3%	0.8	1.1	38%
BH 5	5,379	7,838	168	202	20%	17	5	-71%	24	16	-33%	9,990	9,831	-2%	0.9	0.5	-44%
Average	*9,537*	*8,569*	*144*	*145*	*1%*	*14*	*24*	*66%*	*42*	*39*	*-8%*	*9,957*	*9,822*	*-1%*	*0.9*	*1.1*	*19%*
Overall Average	***9,929***	***10,567***	***145***	***142***	***-2%***	***24***	***22***	***-7%***	***40***	***33***	***-16%***	***9,921***	***9,749***	***-2%***	***0.83***	***0.84***	***1%***

[1] No statistically significant difference at the 0.05 level.

[2] This value was high by an order of magnitude compared to the other values; thus, it was treated as an outlier and not considered in the analysis.

As it is shown in Table 6 and Figures 12 through 17, even though there was a statistically significant difference in emissions rates between the two fuels in most cases, neither fuel type had emissions rates that were consistently higher or lower than the other fuel type. For example, the average NO_x emission rate for BH 4 was 15% lower for B20 than petroleum diesel; however, for BH 5, the average NO_x emission rate was 20% higher for B20 than for petroleum diesel. These types of mixed results appeared throughout the data for each pollutant and each type of equipment. For all 15 items of equipment, however, results showed that B20 resulted in average emissions rates reductions of 2% in NO_x, 7% in HC, 16% in CO, and 2% in CO_2, compared to petroleum diesel; there was an overall average increase of 1% in PM emission rates for B20 compared to petroleum diesel. More graphical charts are shown in the appendix to provide the difference between B20 and petroleum diesel emission rates.

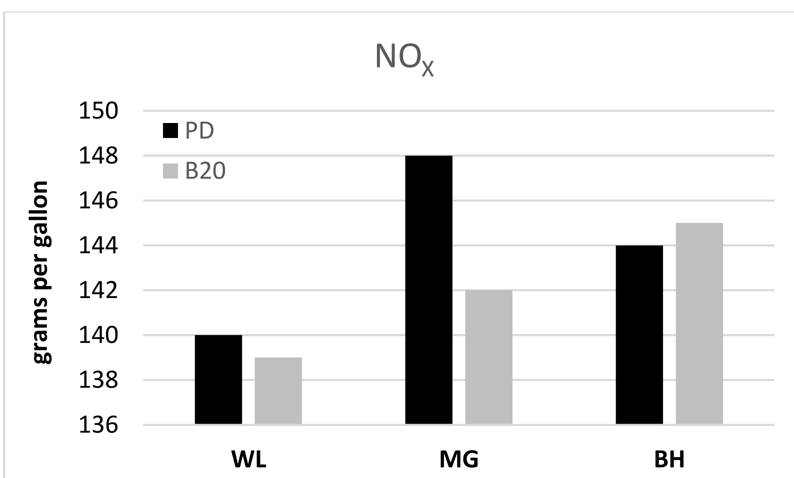


Figure 12. Comparison of Average NO_x Emissions Rates of B20 Biodiesel versus Petroleum Diesel for Different Equipment

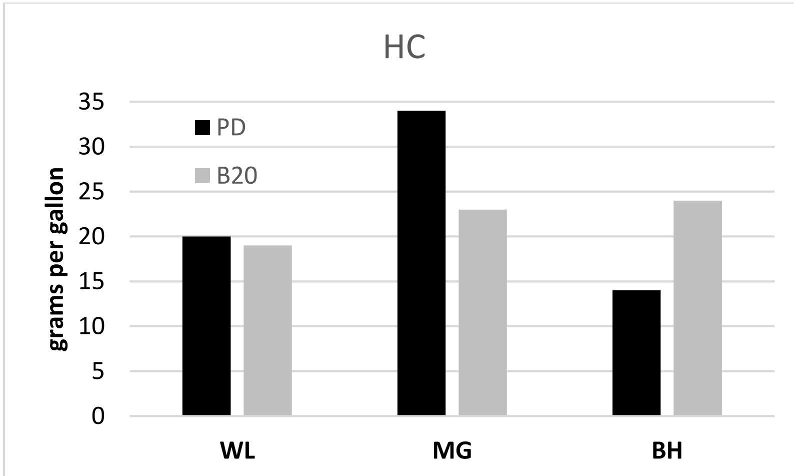


Figure 13. Comparison of Average HC Emissions Rates of B20 Biodiesel versus Petroleum Diesel for Different Equipment

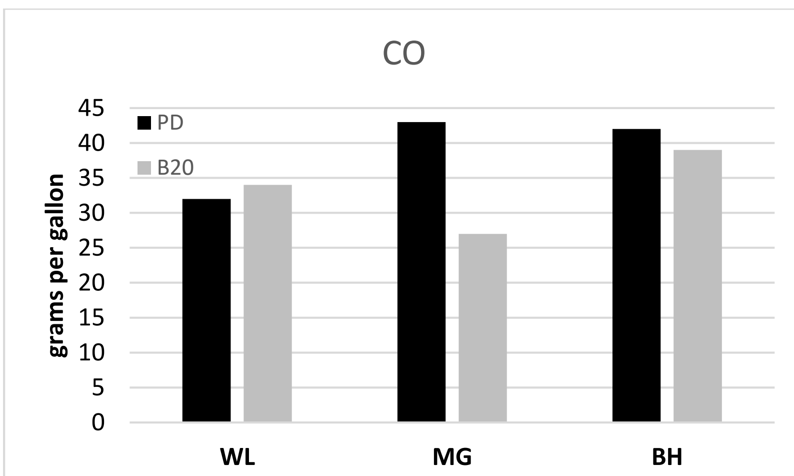


Figure 14. Comparison of Average CO Emissions Rates of B20 Biodiesel versus Petroleum Diesel for Different Equipment

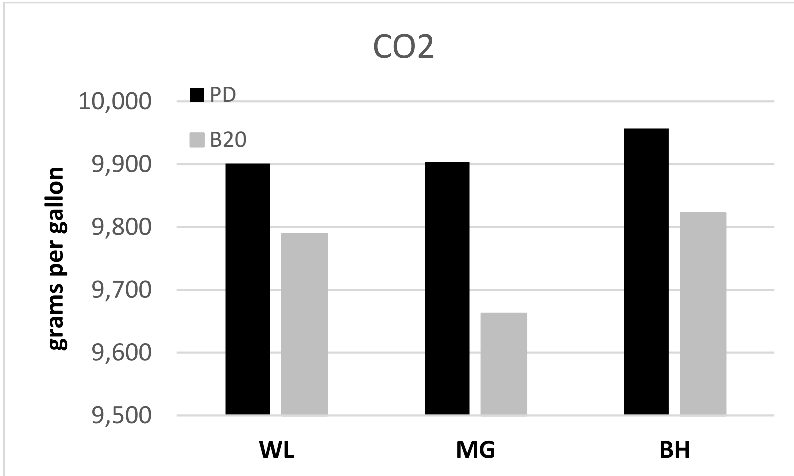


Figure 15. Comparison of Average CO_2 Emissions Rates of B20 Biodiesel versus Petroleum Diesel for Different Equipment

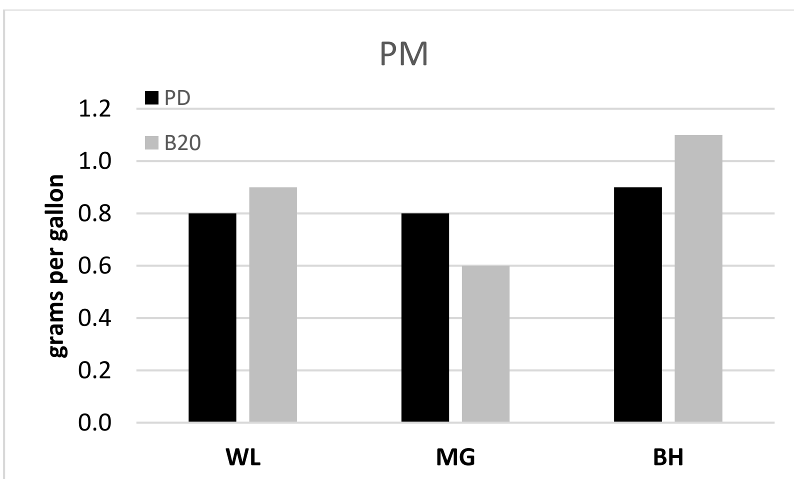


Figure 16. Comparison of Average PM Emissions Rates of B20 Biodiesel versus Petroleum Diesel for Different Equipment

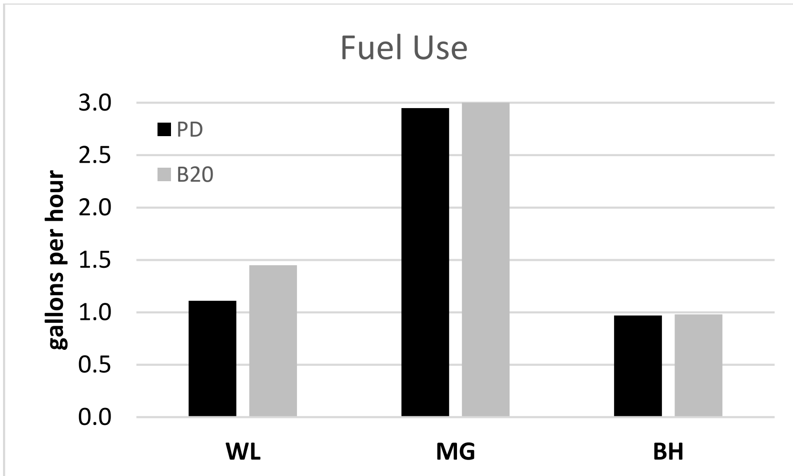
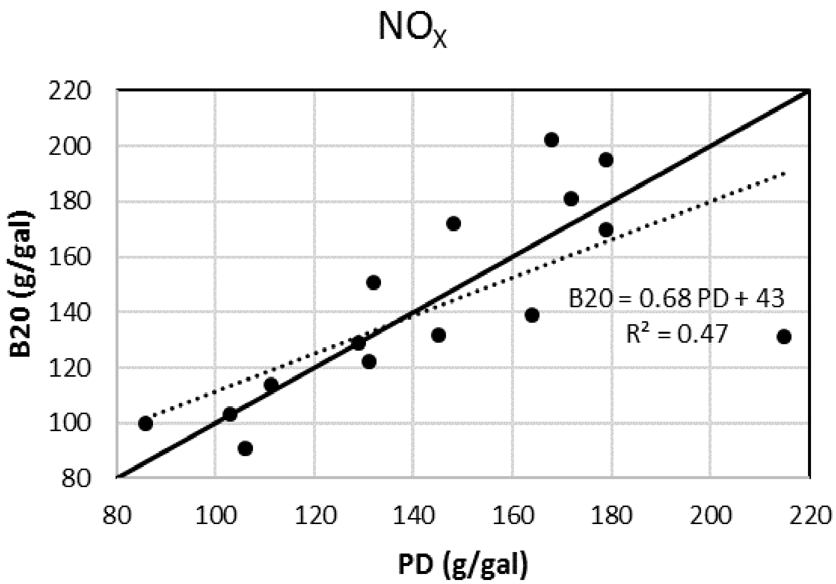
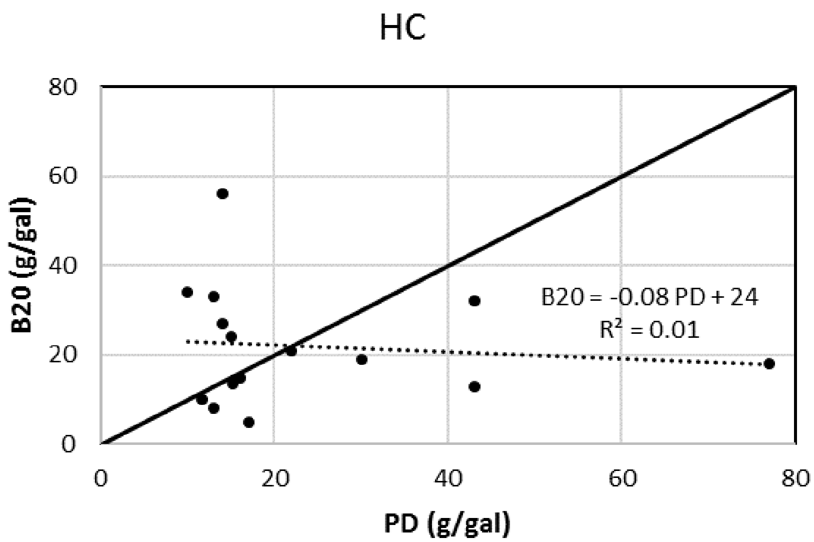


Figure 17. Comparison of Average Fuel Use of B20 Biodiesel versus Petroleum Diesel for Different Equipment

Figures 18 and 19 provide a graphical comparison of emissions rates of each pollutant for B20 versus petroleum diesel. These scatterplots characterize the variability in the emissions data for the two fuels. Only CO emissions had a strong positive correlation ($r = 0.81$) between the two fuel types. There was a moderate positive correlation ($r = 0.69$) between B20 and petroleum diesel emissions rates of NO_x. For HC, CO_2, and PM, there were very low correlations between B20 and petroleum diesel. Furthermore, there was no clear distinction in the data that showed which fuel type yielded the higher average emissions rates for the most items of equipment. For example, average NO_x emissions rates for B20 were higher than petroleum diesel for seven items of equipment, lower for six items of equipment, and about the same for two items of equipment. HC, CO, and PM emissions rates had similar distributions; however, CO_2 emissions rates for B20 were lower than petroleum diesel for 12 of the 15 items of equipment.





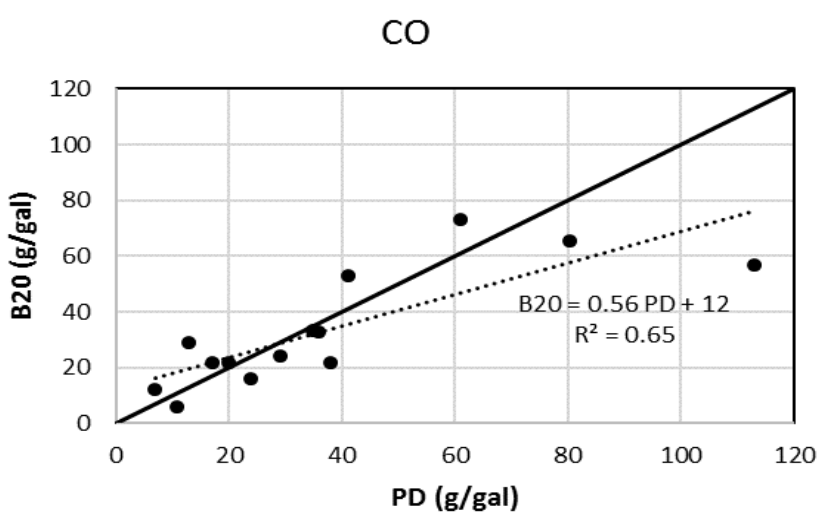
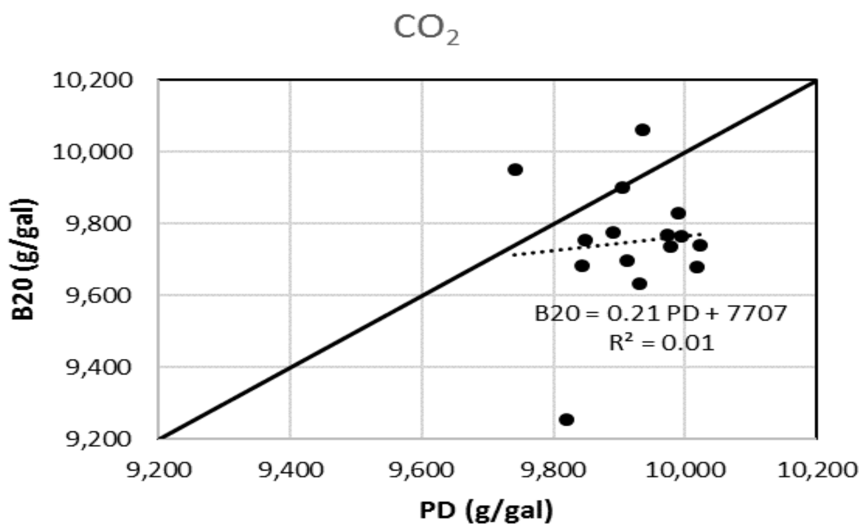


Figure 18. Comparison of Average Emissions Rates of NO_x, HC, and PM



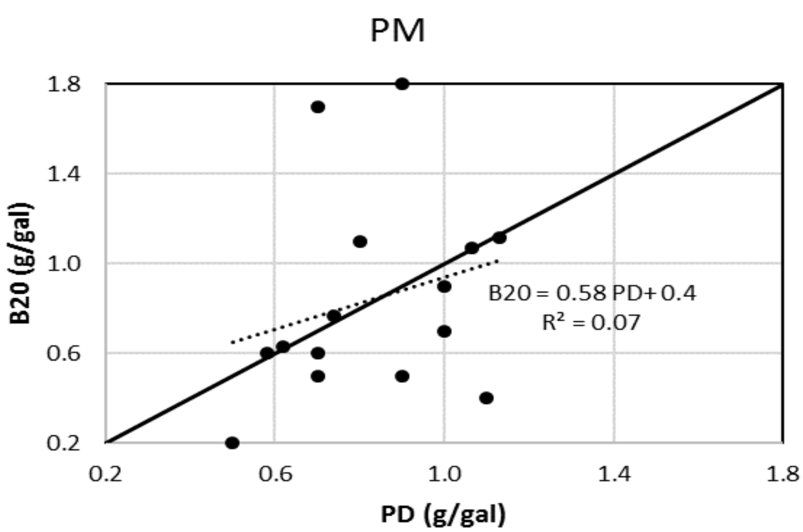
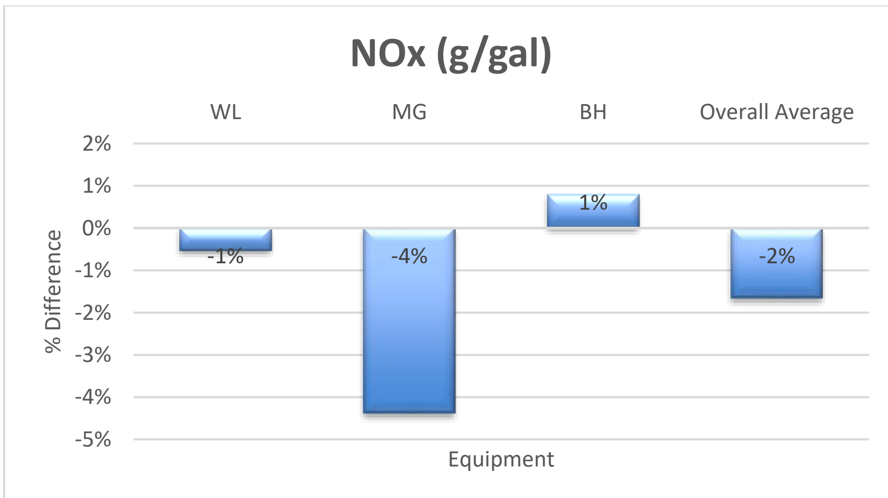
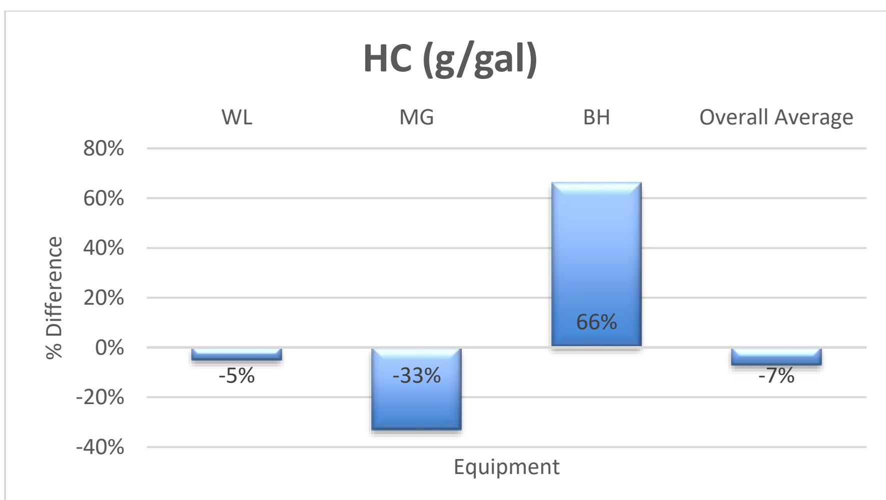
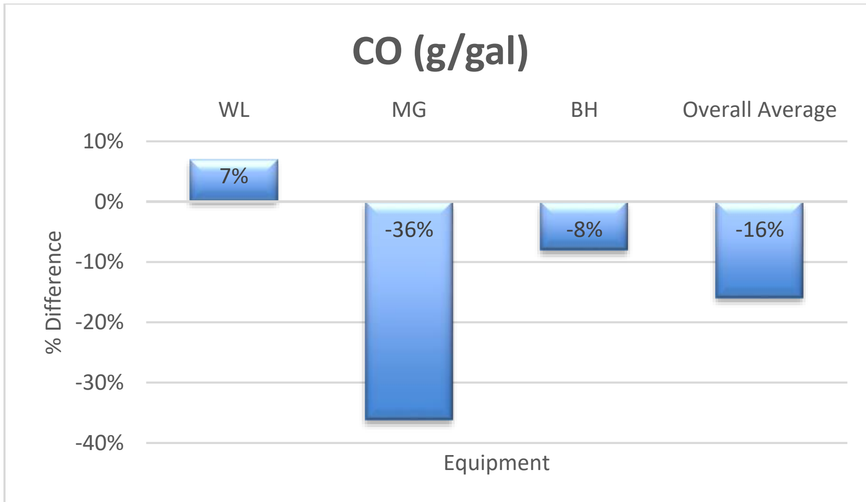


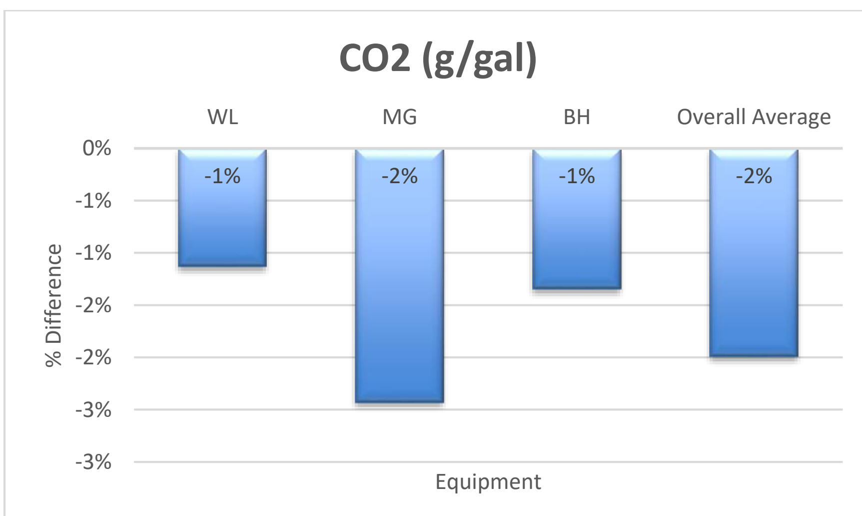
Figure 19. Comparison of Average Emissions Rates of CO_2 and PM

Percentage of the difference of average emissions rates for B20 biodiesel compared to petroleum diesel in each equipment type and overall average are shown in the following figures.






CO (g/gal)
WL
MG
BH
Overall Average
10%
0%
-10%
-20%
-30%
-40%
% Difference
7%
-36%
-8%
-16%
Equipment


CO2 (g/gal)
WL
MG
BH
Overall Average
0%
-1%
-1%
-2%
-2%
-3%
-3%
% Difference
-1%
-2%
-1%
-2%
Equipment

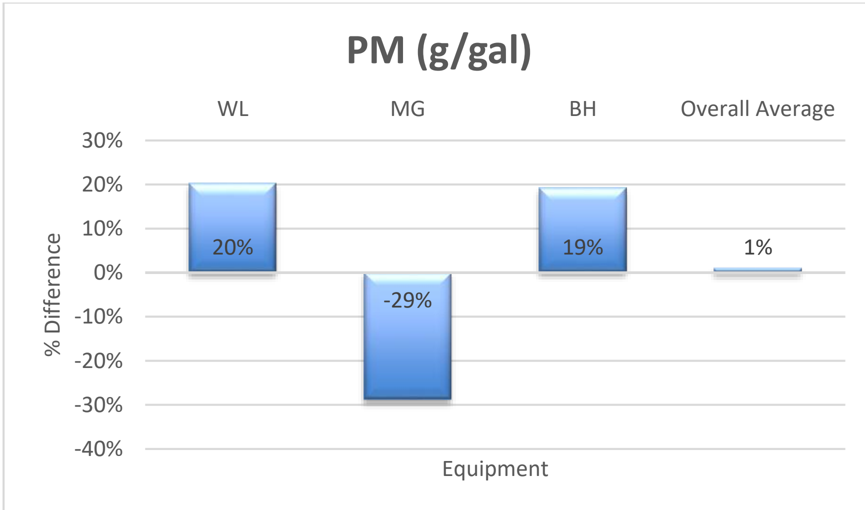


Figure 20. Percentage of Difference of Average Emissions Rates for B20 Biodiesel Compare to Petroleum Diesel

3.2.2.3.1. Discussion

With respect to environmental impacts, the results of the case study showed differences between B20 and petroleum diesel in the average emissions rates of NO_x, HC, CO, CO_2, and PM. Although several individual items of equipment had increases in emissions rates when using B20, the overall average of all equipment represented a decrease of 2% in NO_x, 7% in HC, 16% in CO, and 2% in CO_2. There was an overall average increase of 1% in PM emissions when using B20 versus petroleum diesel (figure 16). Even though the differences in average emissions rates between B20 and petroleum diesel appear modest, they were statistically significant in most cases. In spite of the slight increase in PM, the general conclusion is that B20 had a positive environmental impact compared to petroleum diesel based on reductions in emissions of NO_x, HC, CO, and CO_2 on a gram per gallon basis. Environmentally conscious maintenance equipment fleet managers may choose to use B20 over petroleum diesel due to the potential reductions in emissions of air pollutants and greenhouse gases.

3.3 Assess the Energy and Environmental Impact of Engine Tier Standards (Tier 0 vs. Tier 1 vs. Tier2)

It is a belief that higher tier number results less pollutants and fuel use. In this objective, the same dataset for previous objectives was used to investigate this hypothesis.

3.3.1. Methodology

Environmental impacts were characterized based on emissions rates of NO_x, HC, CO, CO_2, and PM as well as fuel usage. A comprehensive real world and quality assured dataset was obtained from the prior research that was done by Lewis (2009) about construction equipment emissions. Pollutant emission rates were compared to EPA standards for tiers 0,1, and 2 bulldozers and track loaders, and tiers 0,1,2, and 3 motor graders on petroleum diesel. From every tier of each equipment type, just one equipment was selected to represent that specific tier. The criteria for the selection was having close horsepower to eliminate engine attributes effects other than tier number. Cumulative

Frequency Diagram (CFD) was plotted as well to see how much data are below and above EPA standards. Also, one way ANOVA test and Tukey test with 95% of confidence have been done with Minitab software to see if pollutant emission rates and fuel use are significantly different for different tiers or not.

3.3.2. Results

I normalized the EPA standard for each tier of each pollutant as well as emission rates in order to show different ranges of data for different equipment in one graph. I used equation (3-1) in order to normalize data:

$$X_n = (X_i - X_{min})/(X_{max} - X_{min}) \qquad (3\text{-}1)$$

Where:

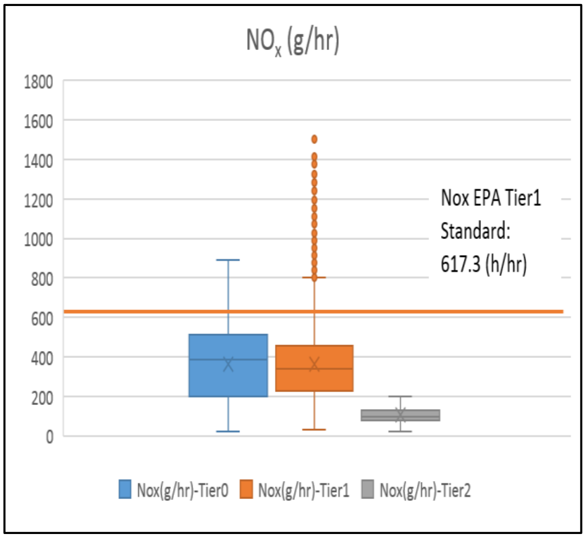
X_n= Normalized variable

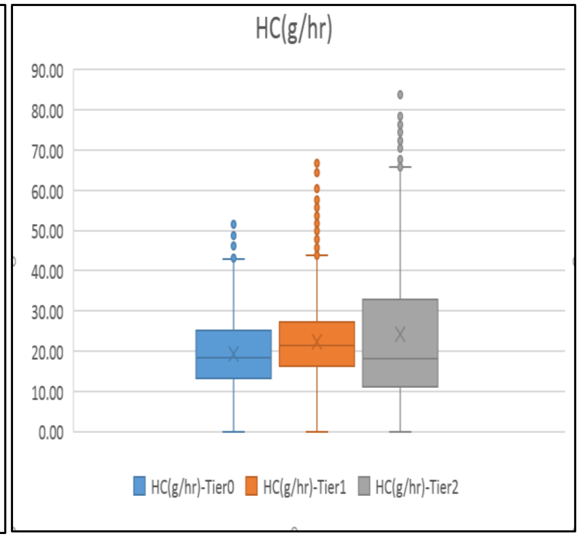
X_i= Variable

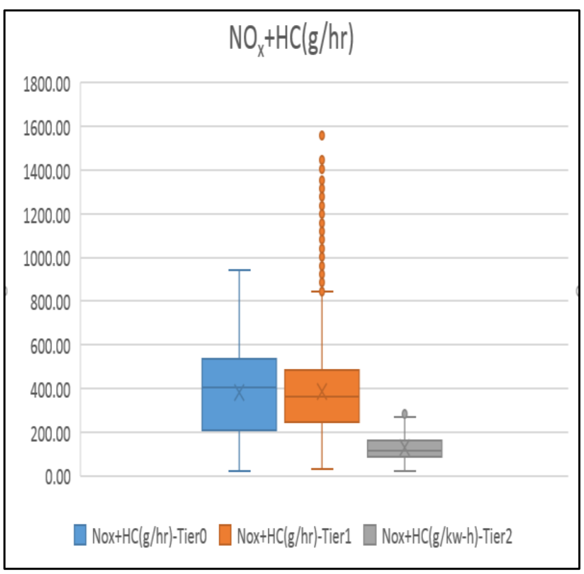
X_{min}= Minimum variable

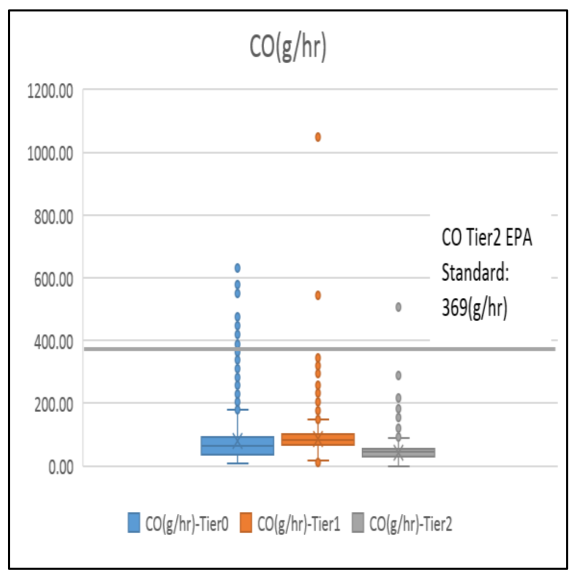
X_{max}= Maximum variable

Then I compared different tier's pollutant rates of the same equipment type in a boxplot diagram. From this diagram, it can be seen how many percentages of pollutants are below the EPA standard. Boxplot figures are shown in the following.


NOx (g/hr)
1800
1600
1400
1200
1000
800
600
400
200
0
Nox EPA Tier1
Standard:
617.3 (h/hr)
Nox(g/hr)-Tier0
Nox(g/hr)-Tier1
Nox(g/hr)-Tier2


HC(g/hr)
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
HC(g/hr)-Tier0
HC(g/hr)-Tier1
HC(g/hr)-Tier2


NOx+HC(g/hr)
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
Nox+HC(g/hr)-Tier0
Nox+HC(g/hr)-Tier1
Nox+HC(g/kw-h)-Tier2


CO(g/hr)
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
CO Tier2 EPA
Standard:
369(g/hr)
CO(g/hr)-Tier0
CO(g/hr)-Tier1
CO(g/hr)-Tier2

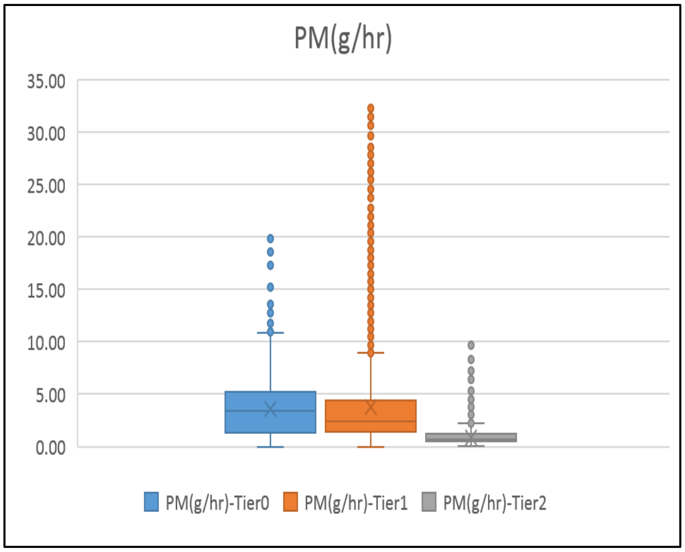
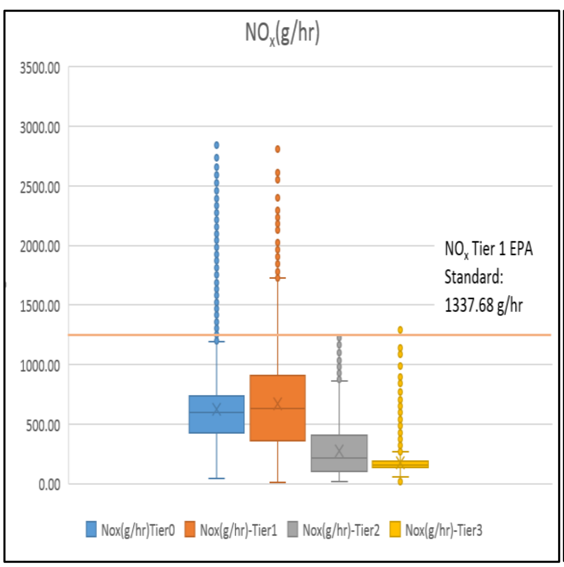
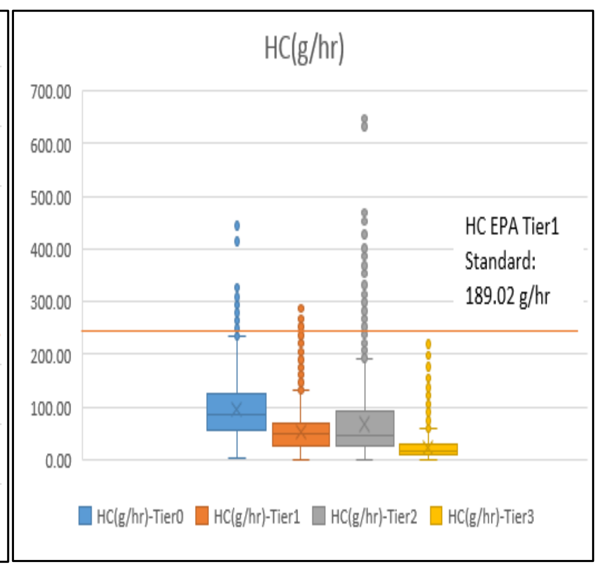
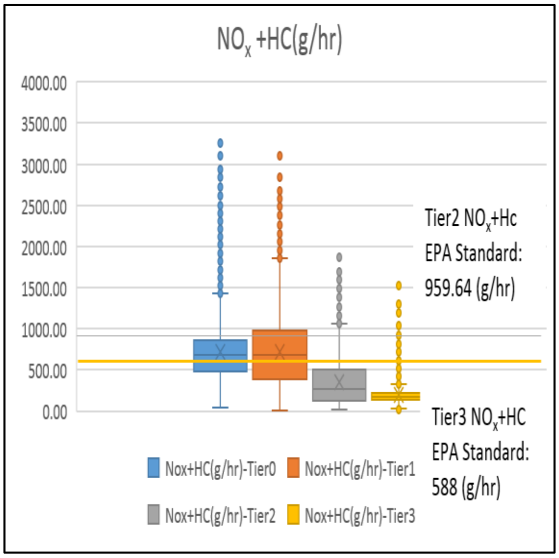
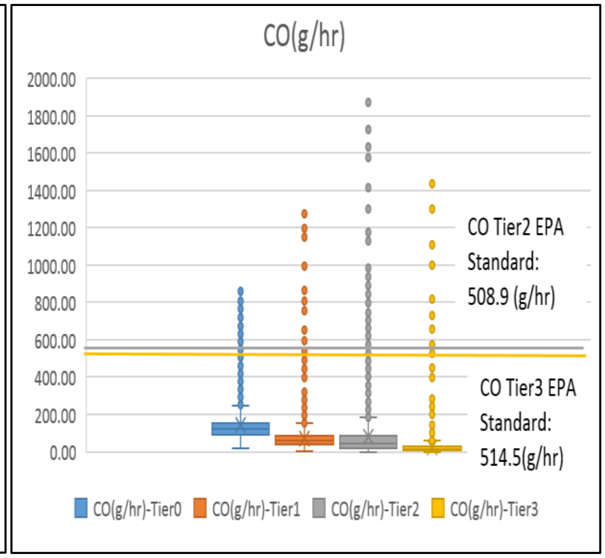


Figure 21. Boxplot Comparison of Pollutant Rates for Different Tiers of Dozers with Normalized EPA Standard









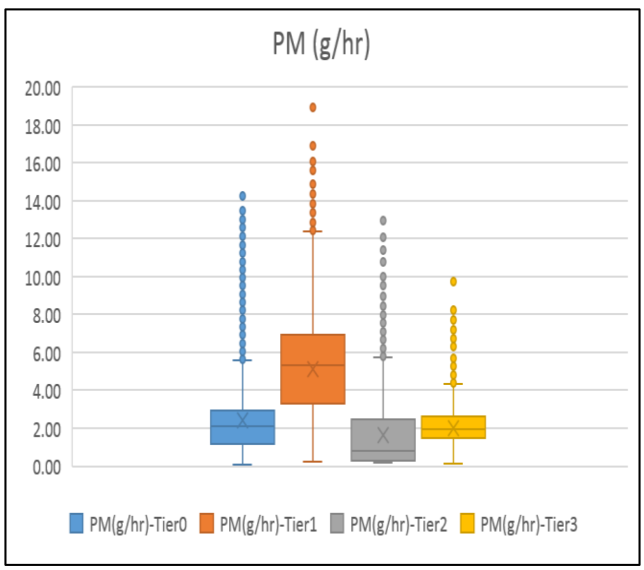
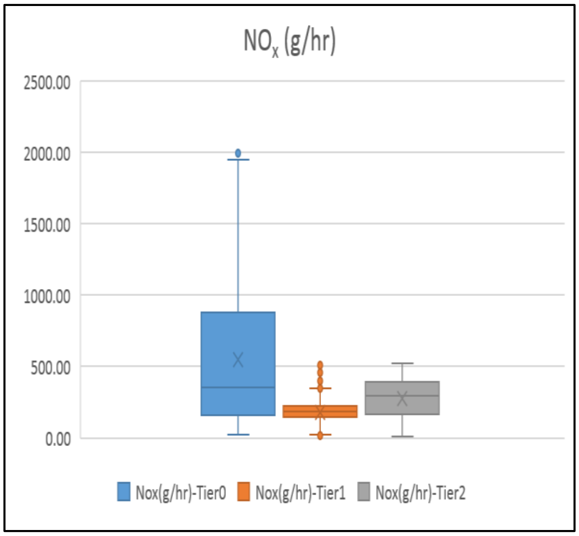
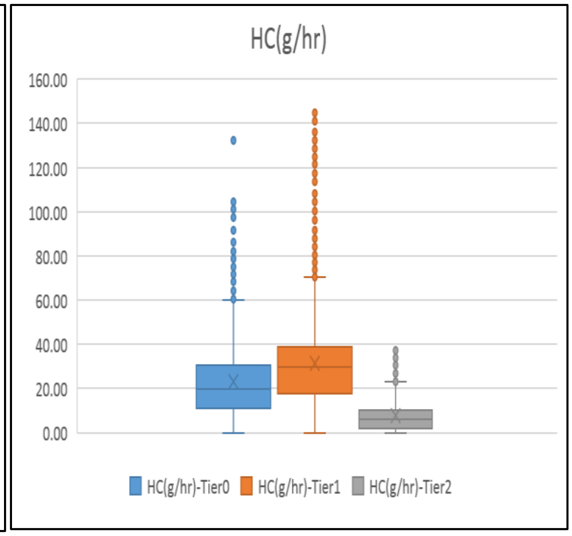
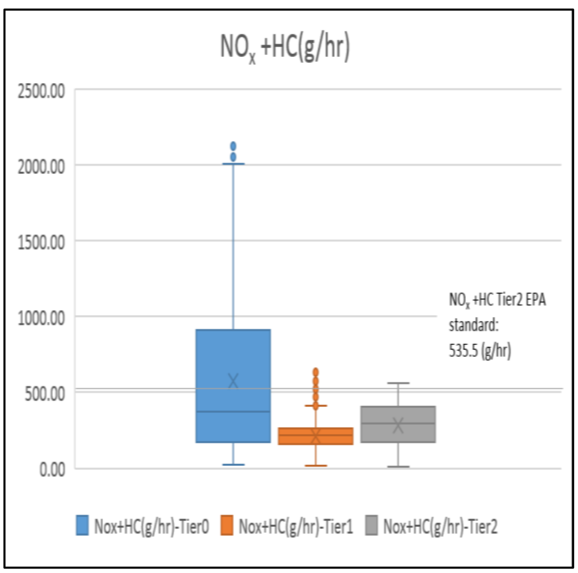
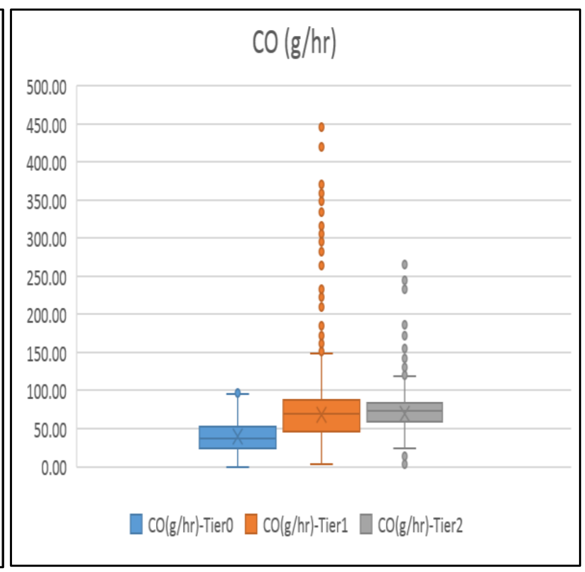


Figure 22. Boxplot Comparison of Pollutant Rates for Different Tiers of Motor Graders with Normalized EPA Standard


NOx (g/hr)
2500.00
2000.00
1500.00
1000.00
500.00
0.00
Nox(g/hr)-Tier0
Nox(g/hr)-Tier1
Nox(g/hr)-Tier2


HC(g/hr)
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
HC(g/hr)-Tier0
HC(g/hr)-Tier1
HC(g/hr)-Tier2


NOx +HC(g/hr)
2500.00
2000.00
1500.00
1000.00
500.00
0.00
NOx +HC Tier2 EPA standard: 535.5 (g/hr)
Nox+HC(g/hr)-Tier0
Nox+HC(g/hr)-Tier1
Nox+HC(g/hr)-Tier2


CO (g/hr)
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
CO(g/hr)-Tier0
CO(g/hr)-Tier1
CO(g/hr)-Tier2

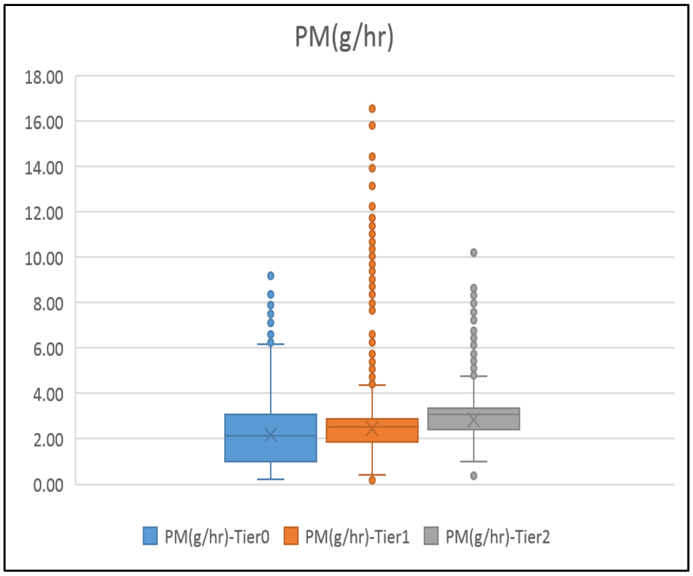


Figure 23. Boxplot Comparison of Pollutant Rates for Different Tiers of Trackloaders with Normalized EPA Standard

Cumulative Frequency Diagram (CFD) was plotted for each pollutant on a gram per hour basis for selected equipment which is brought in appendix F. Also, emission rates were compared with EPA engine tier standards. The summary of results is shown in table7.

Table 6. Summary of Comparison Between emission rates and EPA engine tier standards

Equipment	Tier	NO_x EPA Standard (g/hr)	NO_x(g/hr)	HC EPA Standard (g/hr)	HC(g/hr)	Nox+HC EPA Standard (g/hr)	NO_x+ HC(g/hr)	CO EPA Standard (g/hr)	CO(g/hr)	PM EPA Standard (g/hr)	PM(g/hr)
Dozer	1	617.3	Above EPA Standard-10% of the time	-	-	-	-	-	-	-	-
	2	-	-	-	-	553.5	Below EPA Standard	369	Below EPA Standard except 1 time!	29.52	Below EPA Standard
MG	1	1337.68	Above EPA Standard-5% of the time	189.02	Above EPA Standard-2% of the time	-	-	1657.56	Above EPA Standard-3% of the time	78.516	Below EPA Standard
	2	-	-	-	-	959.64	Above EPA-2.5% of the time	508.9	Above EPA Standard-1.5% of the time	29.08	Below EPA Standard
	3	-	-	-	-	588	Above EPA-2% of the time	514.5	Above EPA Standard-1% of the time	29.4	Below EPA Standard
TL	1	829.84	Below EPA Standard	-	-	-	-	-	-	-	-
	2	-	-	-	-	625.02	Below EPA Standard	473.5	Below EPA Standard	28.41	Below EPA Standard

As shown in the table, NO_x is above EPA standards for tier 1 bulldozer and motor grader. HC is above the EPA standard in just one case that is tier 1 motor grader. NO_x +HC is higher than the standard for tiers 2 and 3 motor graders. CO is above EPA standard in most cases for different tiers of motor graders and bulldozers. However, PM always stays below the EPA standard for all equipment types and tiers. Results show that CO has more cases above the EPA standard, but NO_x has the highest period of time above the EPA standard.

Results on equipment type basis show track loader emission rates for all pollutants are below EPA standard and motor grader has the most cases of passing EPA standard.

In addition, pollutant emission rates and fuel use rates of the same equipment are provided in table 8.

Table 7. Summary of Emission Rates and Fuel Use Rates

Equipment	EPA Engine Tier	N (sec.)	Fuel (gal/hr)	No_x		HC		CO		CO_2		PM	
				(g/gal)	(g/hr)	(g/gal)	(g/hr)	(g/gal)	(g/hr)	(g/gal)	(g/hr)	(g/gal)	(g/hr)
Dozer 1	0	3011	7850.40	363.99	360.85	18.72	24.10	77.92	80.03	9960.14	24666.00	3.78	3.58
Dozer 3	1	9462	7306.10	163.35	364.06	11.69	22.30	51.44	85.66	9957.53	22943.00	1.48	3.73
Dozer 6	2	5085	3584.50	107.67	104.17	25.42	19.20	45.47	43.52	9931.32	11208.10	0.98	0.91
MG4	0	9476	9706.60	377.37	623.76	38.82	96.16	62.21	141.01	9849.66	30211.00	1.60	2.41
MG1	1	15583	18039.00	126.94	667.41	11.39	53.06	15.43	68.48	10009.70	56855.00	0.99	5.14
MG2	2	5503	8735.00	356.51	276.98	87.95	67.28	104.96	79.42	37663.00	27332.00	2.30	1.64
MG6	3	7094	8537.60	135.79	173.80	19.24	23.07	23.23	21.11	20076.00	26925.00	1.47	1.98
TL2	0	4850	9720.70	160.41	551.63	7.88	22.98	15.66	40.07	10013.00	30655.00	0.83	2.19
TL1	1	5046	9988.60	141.61	180.30	29.52	31.42	57.45	68.58	23841.00	31419.00	2.11	2.46
TL3	2	2416	15491.00	61.55	277.28	1.19	7.80	17.92	69.18	10034.80	48920.00	0.64	2.85

There are some figures in the appendix that show graphical comparisons of emission rates of each pollutant for different tiers and equipment based on equipment or tier. It can be seen that in most cases, emission rates and fuel use for bulldozer decrease in higher tier number. One way ANOVA test and Tukey test with 95% of confidence have been done with Minitab software to see if pollutant emission rates and fuel use are significantly different for different tiers or not. Our Tukey test data was on gram per hour and gram per gallon basis and fuel use on gram per hour basis. Minitab result for motor grader is shown in table 9 as an example. As it is shown, different letters for each tier show HC emission rates are significantly different for different tiers. If means share a letter, then it implies no significant differences among those means.

Table 8. Tukey Pairwise Comparisons of HC Emission Rate for Motor Graders

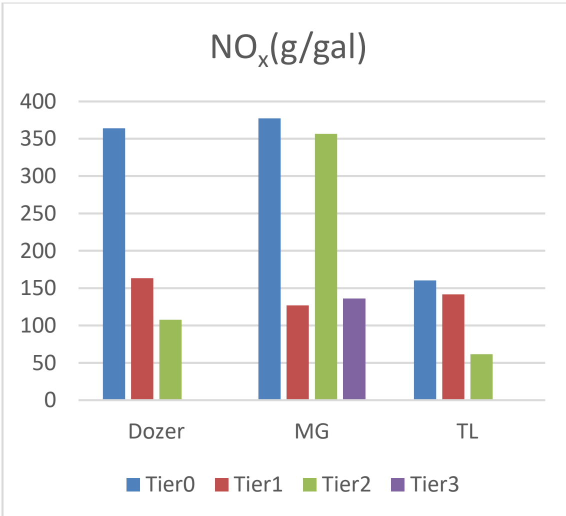
Tukey Pairwise Comparisons

Factor	N	Mean	Grouping			
HC(g/hr)-Tier0 (MG4)	9476	96.159	A			
HC(g/hr)-Tier2 (MG2)	5503	67.283		B		
HC(g/hr)-Tier1 (MG1)	15582	53.060			C	
HC(g/hr)-Tier3 (MG6)	7094	23.070				D

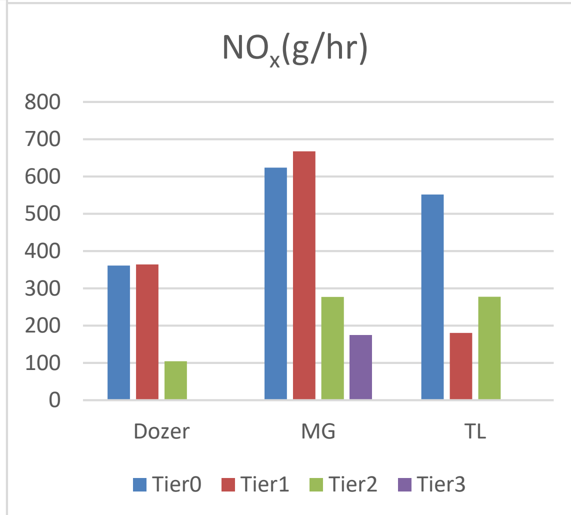
Means that do not share a letter are significantly different.

The tests show that fuel use and most of emission rates are significantly different for different tiers of bulldozers. Except for a few cases, which tier 0 and 1 have close pollutant emission rates like PM (g/hr). Tukey test results are shown in appendixes H, I, and J.

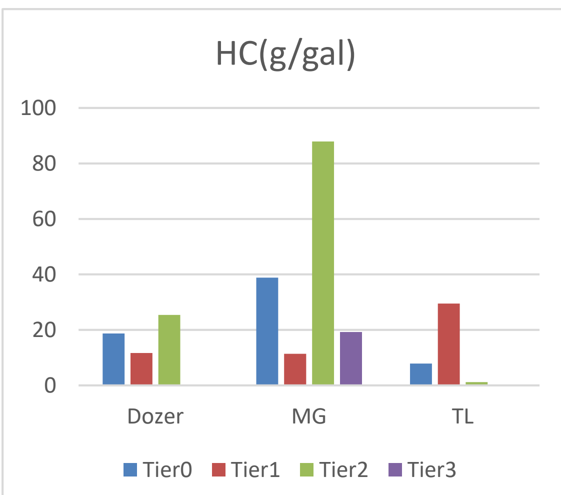
As it can be seen in the following figures, emission rates are getting higher when we go from tier 1 to tier 2 motor grader in most cases. However, fuel use decreases from tier 1 to tier 2 motor grader. Emission rates are less for almost all pollutants and fuel use for tier 3 compare to tier 2. So, there is no clear distinction in the data that shows a higher tier number yields lower emissions rates for the most items of equipment. Nevertheless, it shows that higher tier number has lower fuel use.



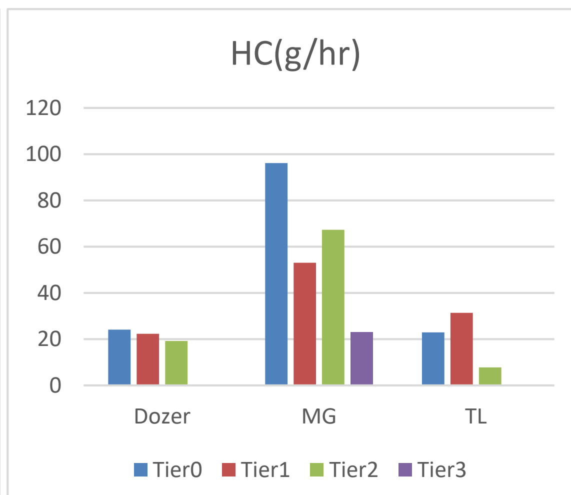
NO$_x$(g/gal)
400
350
300
250
200
150
100
50
0
Dozer
MG
TL
Tier0
Tier1
Tier2
Tier3



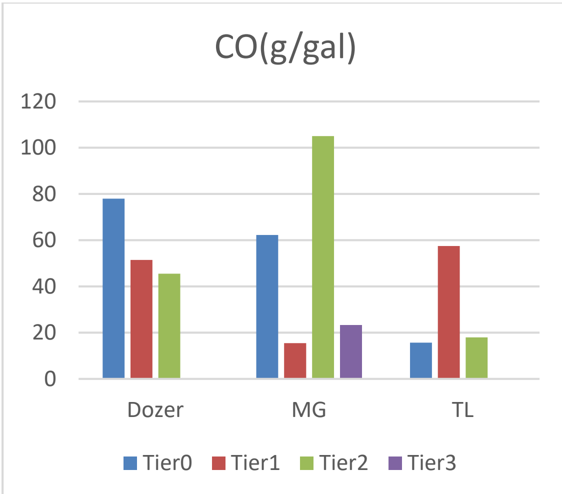
NO$_x$(g/hr)
800
700
600
500
400
300
200
100
0
Dozer
MG
TL
Tier0
Tier1
Tier2
Tier3

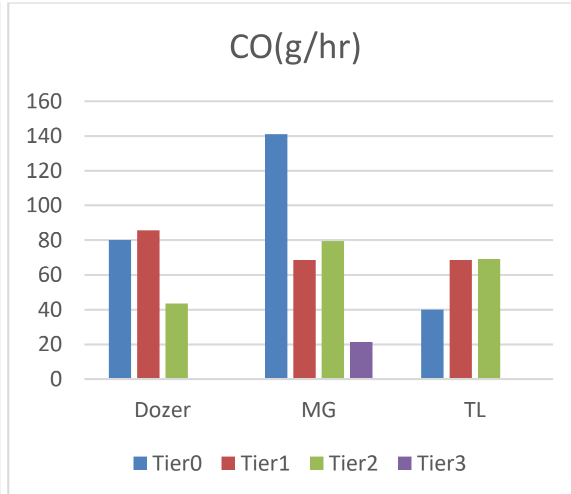


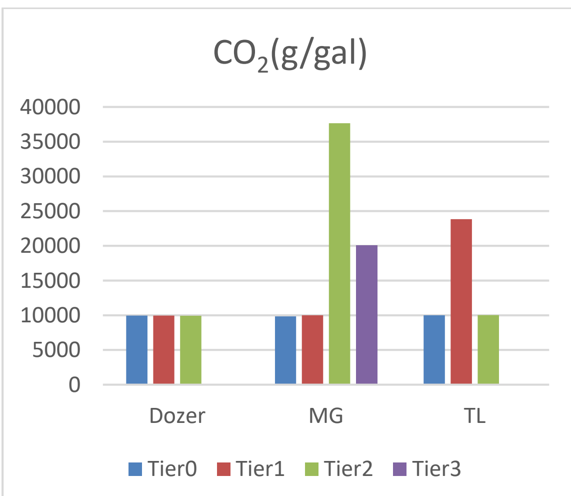
HC(g/gal)
100
80
60
40
20
0
Dozer
MG
TL
Tier0
Tier1
Tier2
Tier3

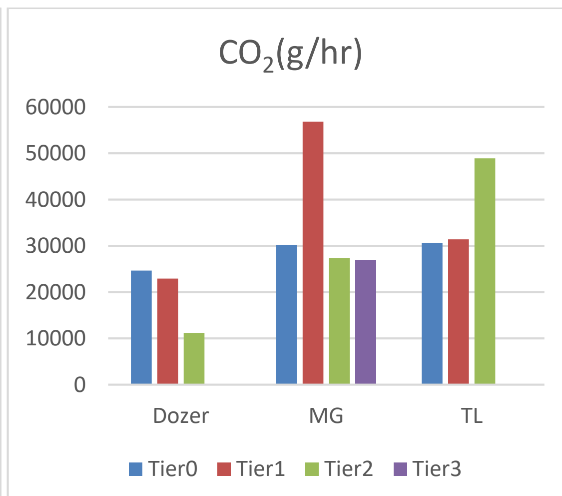


HC(g/hr)
120
100
80
60
40
20
0
Dozer
MG
TL
Tier0
Tier1
Tier2
Tier3


CO(g/gal)
120
100
80
60
40
20
0
Dozer
MG
TL
Tier0 Tier1 Tier2 Tier3


CO(g/hr)
160
140
120
100
80
60
40
20
0
Dozer
MG
TL
Tier0 Tier1 Tier2 Tier3


CO_2(g/gal)
40000
35000
30000
25000
20000
15000
10000
5000
0
Dozer
MG
TL
Tier0 Tier1 Tier2 Tier3


CO_2(g/hr)
60000
50000
40000
30000
20000
10000
0
Dozer
MG
TL
Tier0 Tier1 Tier2 Tier3

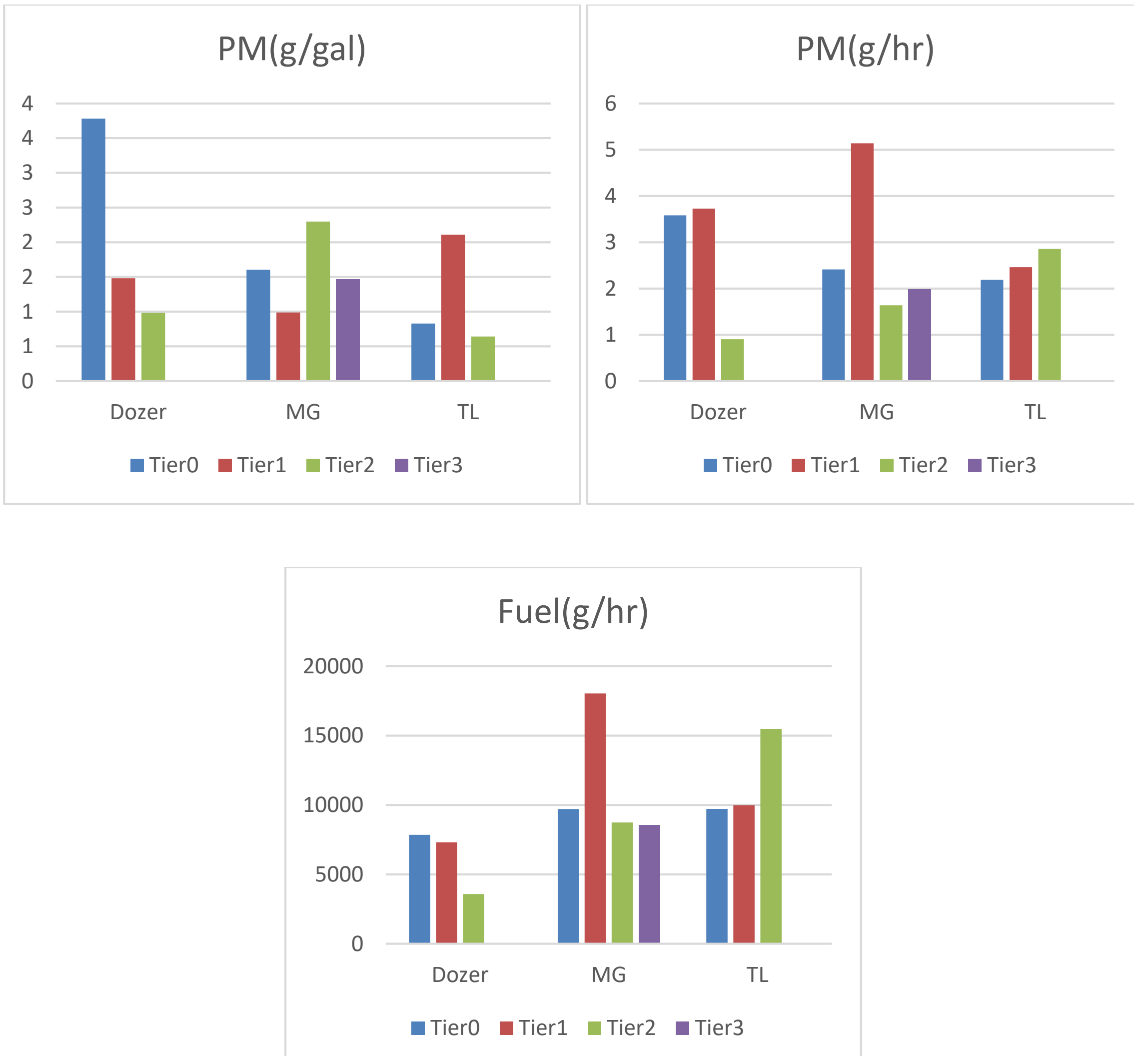


Figure 24. Comparison of Emission Rates and Fuel Use for Different Equipment and Tiers

One-way ANOVA test and Tukey test conclude that again fuel use and the majority of emission rates are significantly different in different tiers of bulldozers. It does not necessarily mean these differences are considered as an advantage for higher tier number.

As we can see in the table and figures, in a lot of cases, higher tier number yields higher pollutant emission rate.

The mixed results appear throughout the data for each pollutant and fuel use for different tiers track loaders. Fuel use is higher in tier 2 track loader compare to tier 1. However, there are less pollutant emission rates in some cases of tier 2 compare to tier 1 track loader like NO_x (g/hr) and vice versa. One-way ANOVA test and Tukey test conclude that most of the pollutant emission rates are significantly different. However, there are significant numbers of results that show no significant difference in fuel use and pollutant emission rates. Emission rates and fuel use for different tiers of all equipment types are shown in figures 25 through 28.

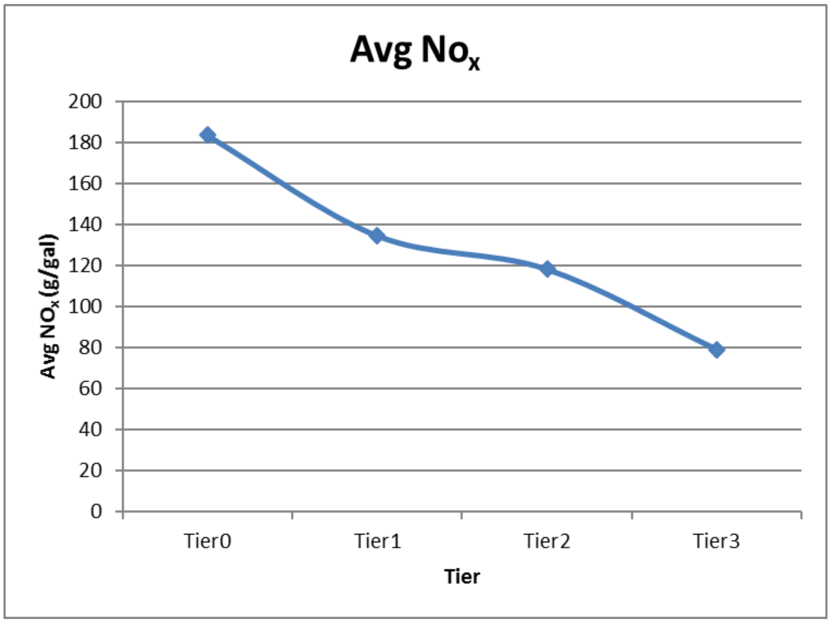


Figure 25.Comparison of Average Emission Rates of NO_x for Different Tiers of all Equipment Types

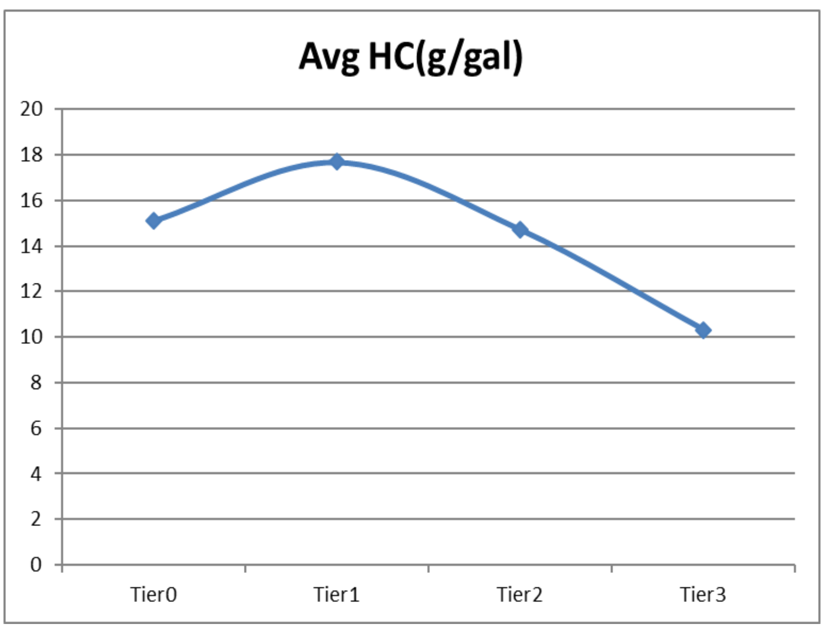


Figure 26. Comparison of Average Emission Rates of HC for Different Tiers of all Equipment Types

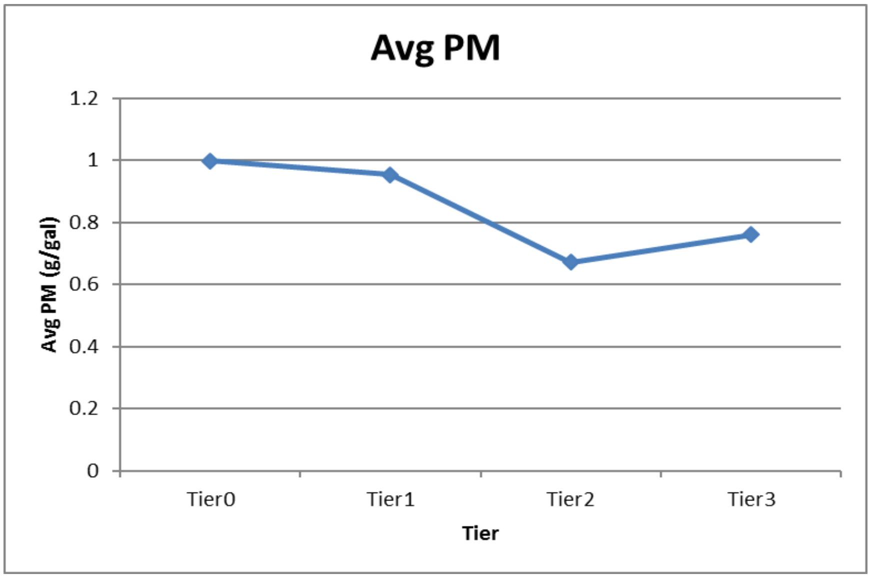


Figure 27. Comparison of Average Emission Rates of PM for Different Tiers of all Equipment Types

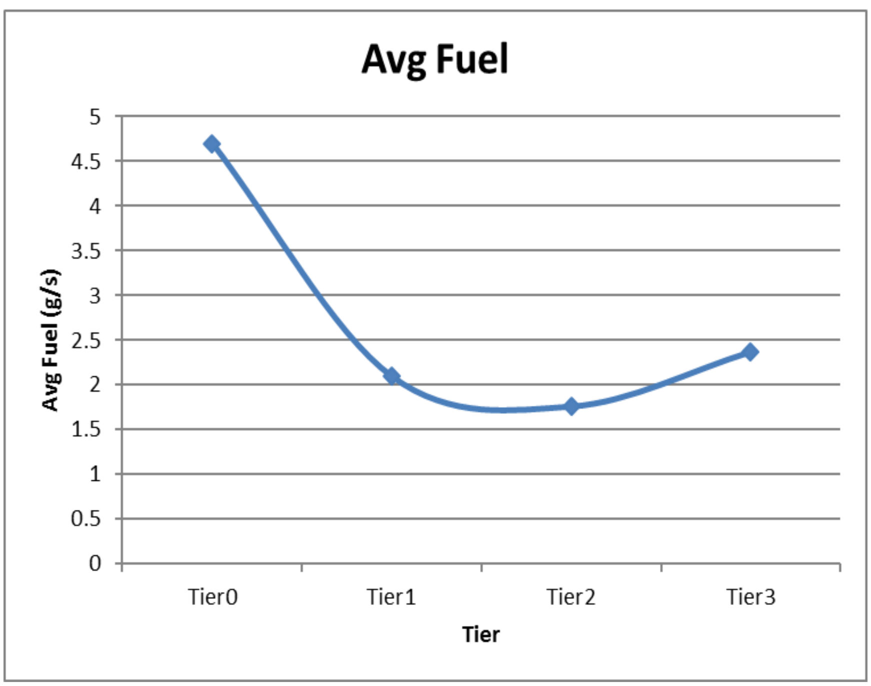


Figure 28. Comparison of Average Fuel Use for Different Tiers of all Equipment Types

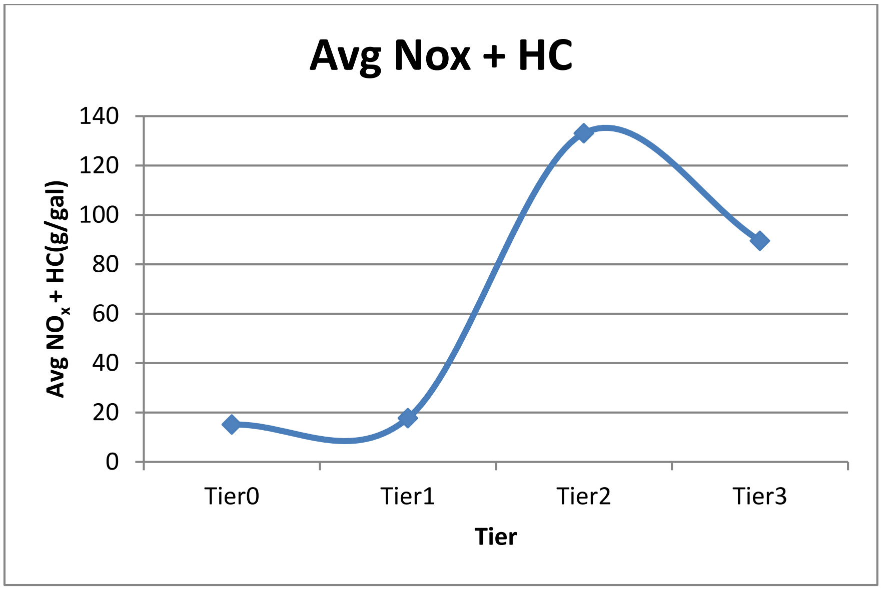
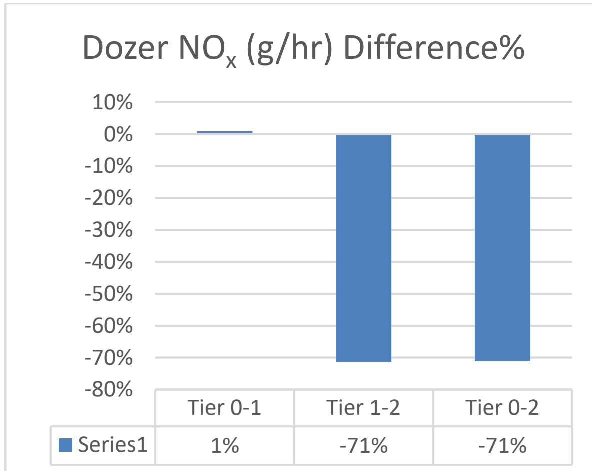
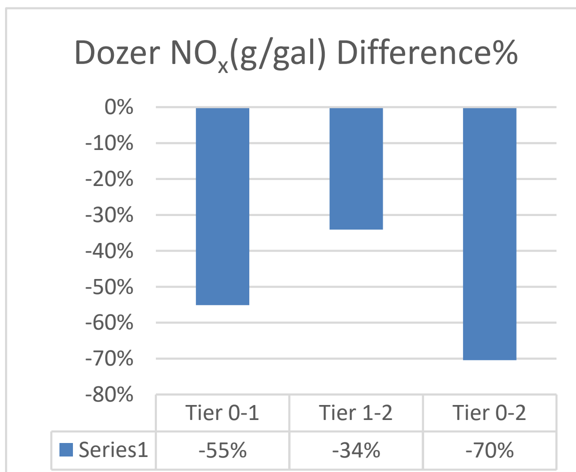


Figure 29. Comparison of Average Emission Rates of NO_x+ HC for Different Tiers of all Equipment Types

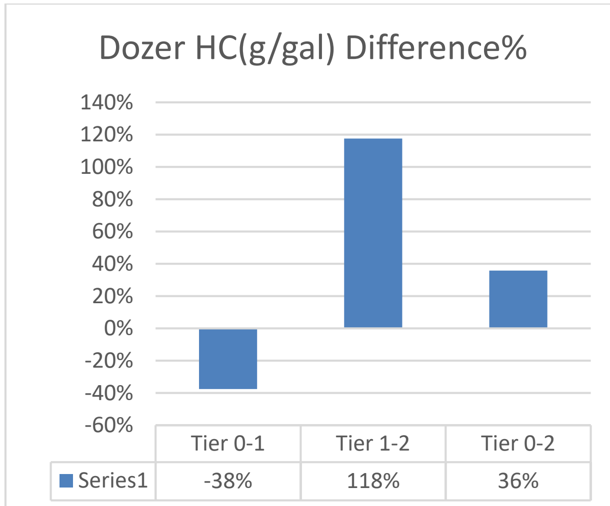
As it is shown in figure 2, the difference percentage of fuel use and emission rates change in higher tier number for each equipment.

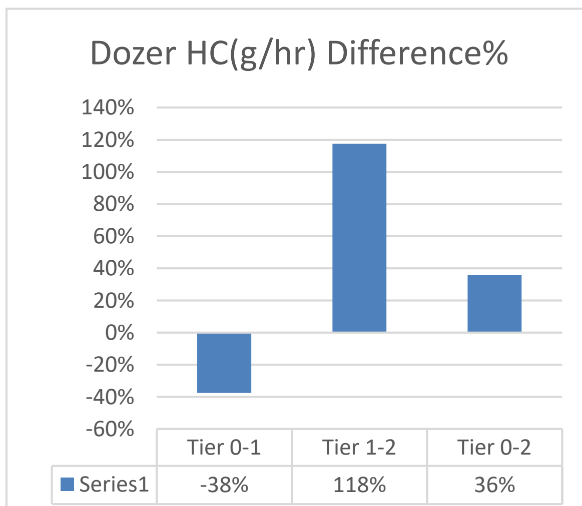


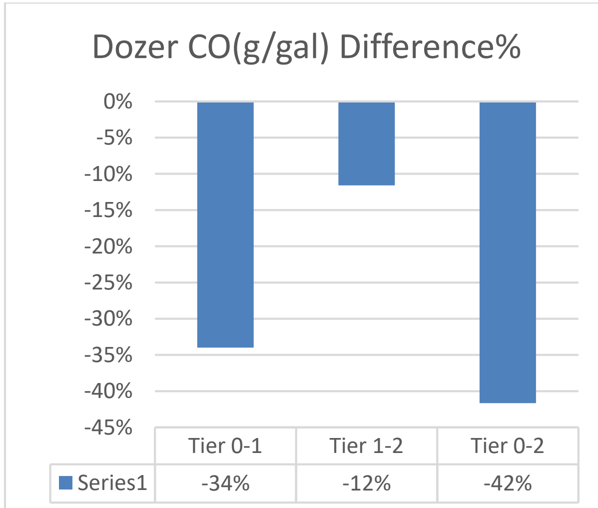
Dozer NO_x (g/hr) Difference%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
1%
-71%
-71%

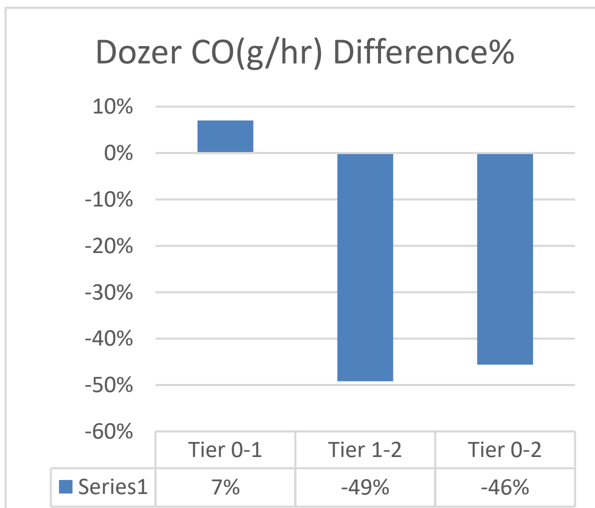


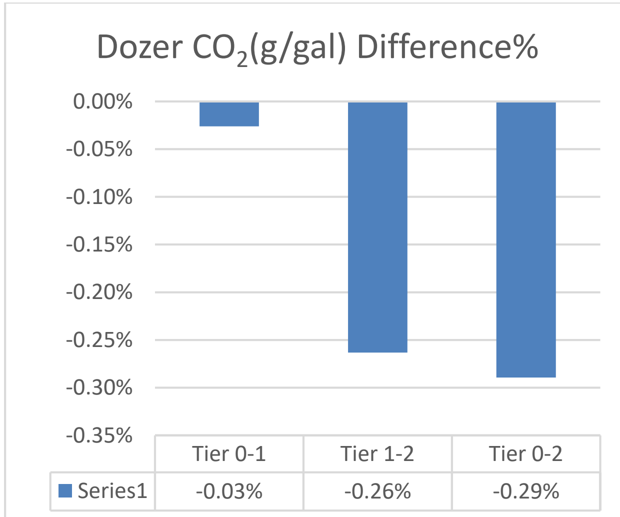
Dozer NO_x(g/gal) Difference%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-55%
-34%
-70%

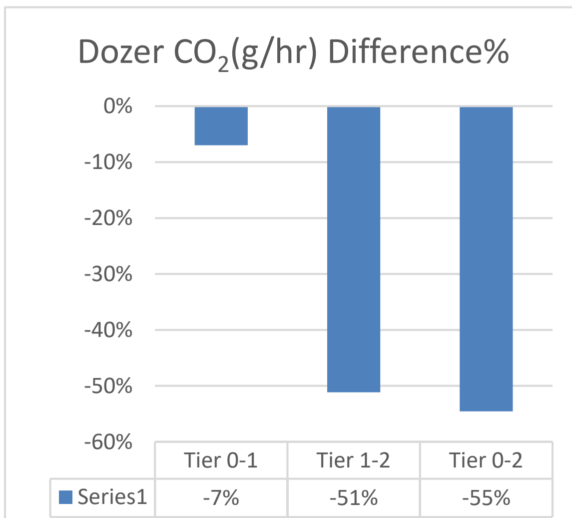

Dozer HC(g/gal) Difference%
140%
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-38%
118%
36%

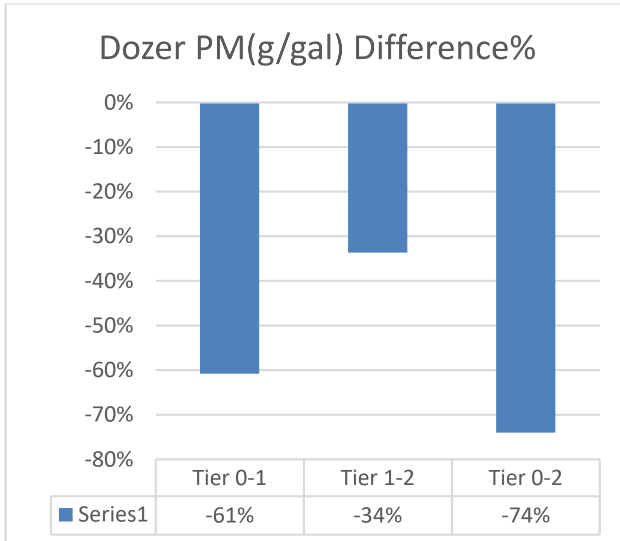

Dozer HC(g/hr) Difference%
140%
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-38%
118%
36%


Dozer CO(g/gal) Difference%
0%
-5%
-10%
-15%
-20%
-25%
-30%
-35%
-40%
-45%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-34%
-12%
-42%

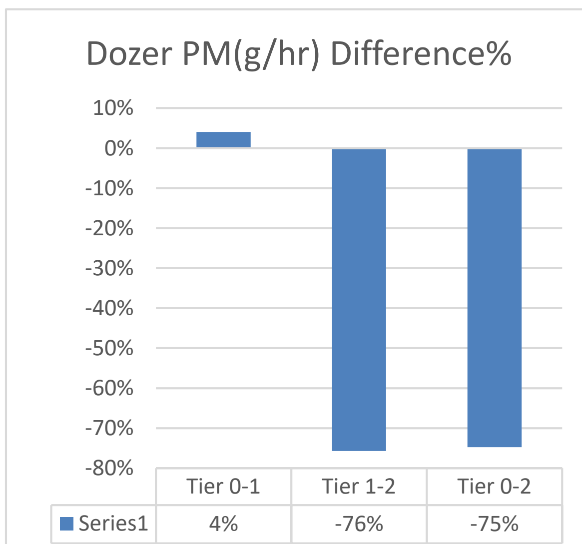

Dozer CO(g/hr) Difference%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
7%
-49%
-46%


Dozer CO_2(g/gal) Difference%
0.00%
-0.05%
-0.10%
-0.15%
-0.20%
-0.25%
-0.30%
-0.35%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-0.03%
-0.26%
-0.29%


Dozer CO_2(g/hr) Difference%
0%
-10%
-20%
-30%
-40%
-50%
-60%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-7%
-51%
-55%



Dozer PM(g/gal) Difference%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-61%
-34%
-74%



Dozer PM(g/hr) Difference%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
4%
-76%
-75%

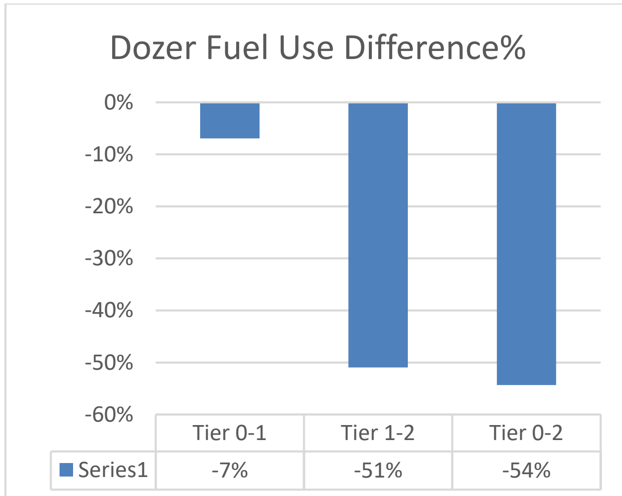
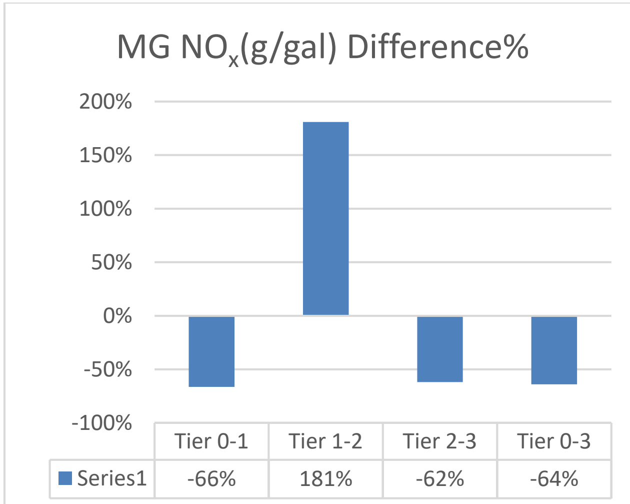
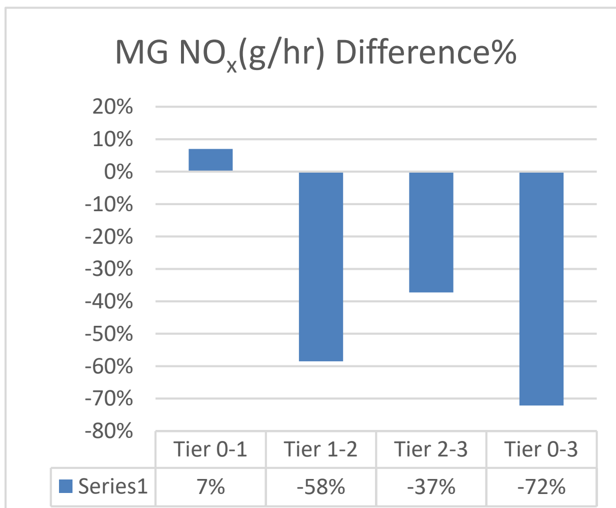
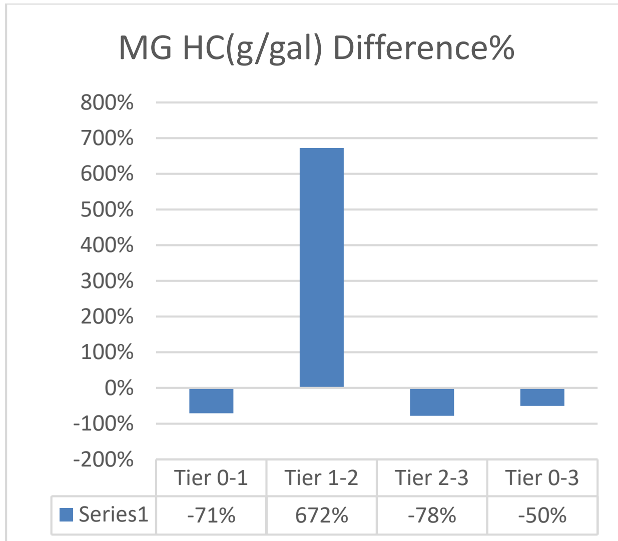
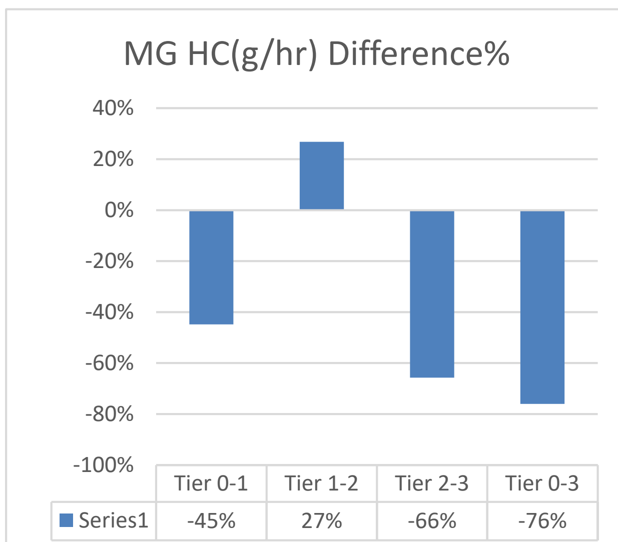


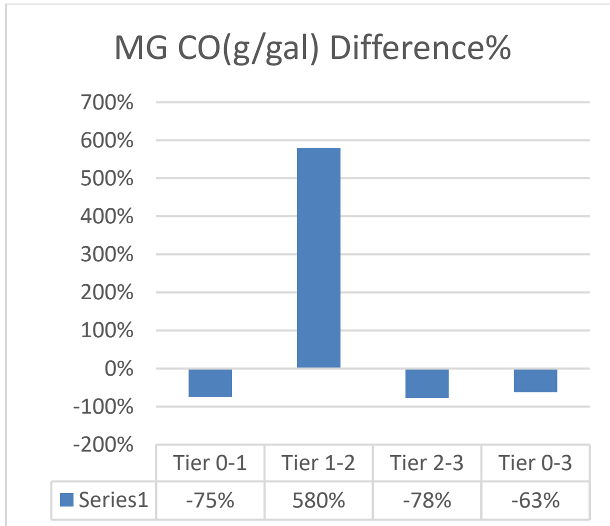
Figure 30. Percentage of Difference in Fuel Use and Emission Rates for Different Tiers of Dozers

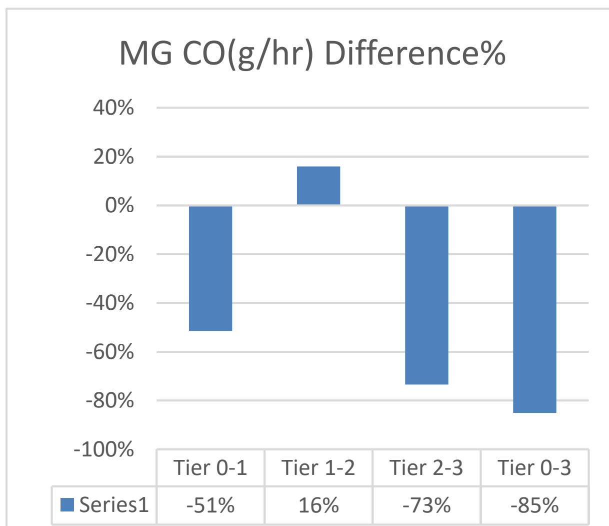

MG NO_x(g/gal) Difference%
200%
150%
100%
50%
0%
-50%
-100%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-66%
181%
-62%
-64%

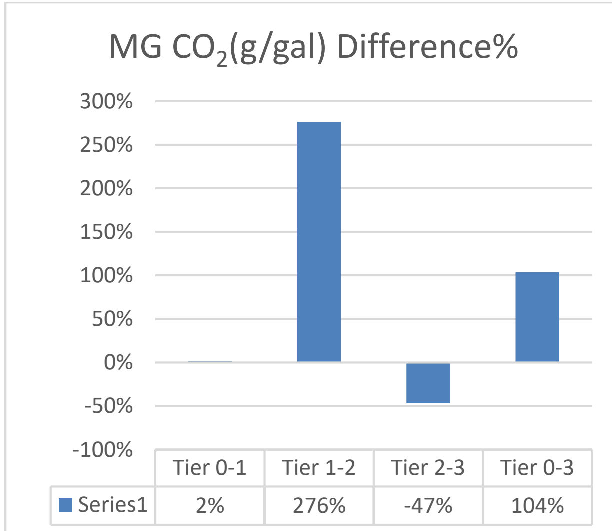

MG NO_x(g/hr) Difference%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
7%
-58%
-37%
-72%

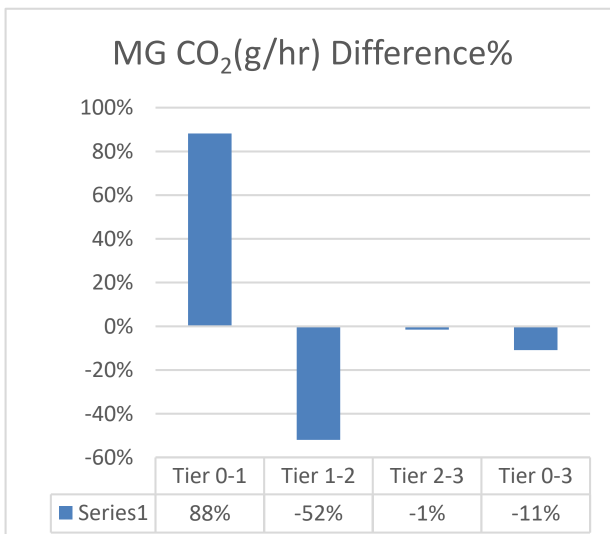

MG HC(g/gal) Difference%
800%
700%
600%
500%
400%
300%
200%
100%
0%
-100%
-200%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-71%
672%
-78%
-50%

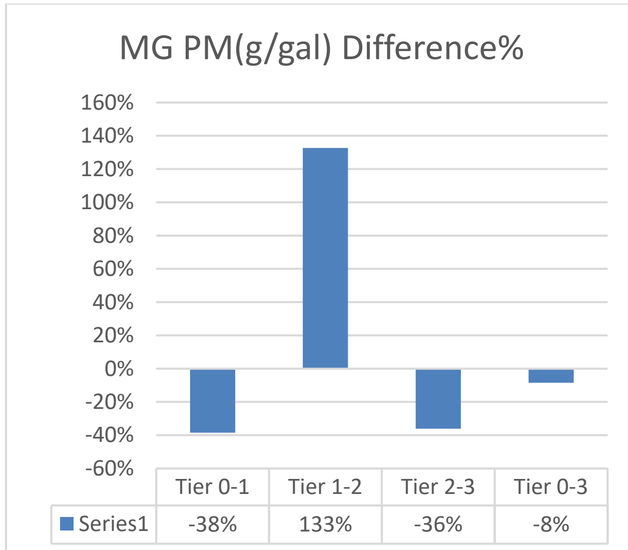

MG HC(g/hr) Difference%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-45%
27%
-66%
-76%

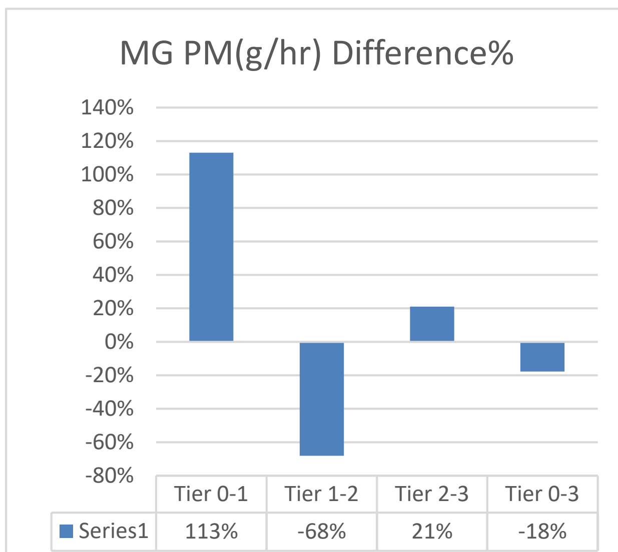

MG CO(g/gal) Difference%
700%
600%
500%
400%
300%
200%
100%
0%
-100%
-200%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-75%
580%
-78%
-63%


MG CO(g/hr) Difference%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-51%
16%
-73%
-85%


MG CO2(g/gal) Difference%
300%
250%
200%
150%
100%
50%
0%
-50%
-100%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
2%
276%
-47%
104%


MG CO2(g/hr) Difference%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
88%
-52%
-1%
-11%


MG PM(g/gal) Difference%
160%
140%
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-38%
133%
-36%
-8%


MG PM(g/hr) Difference%
140%
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
113%
-68%
21%
-18%

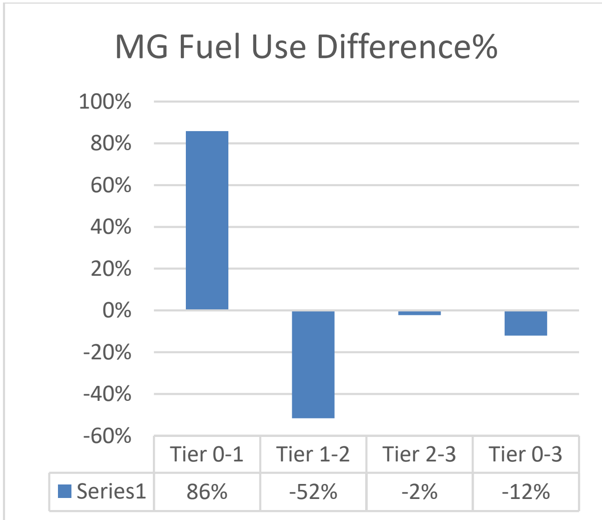
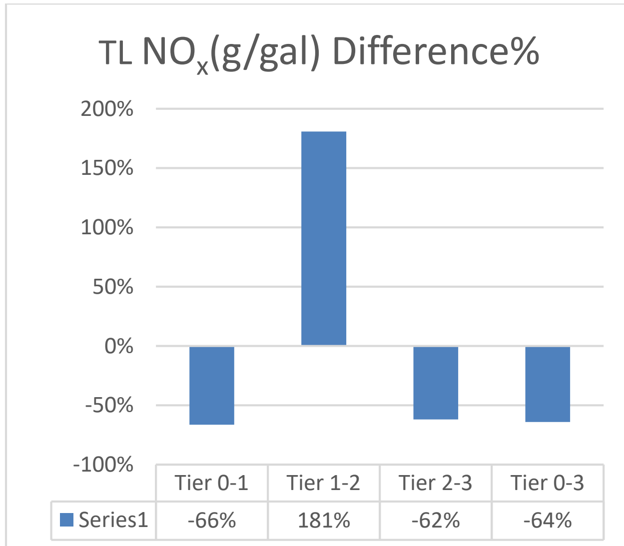
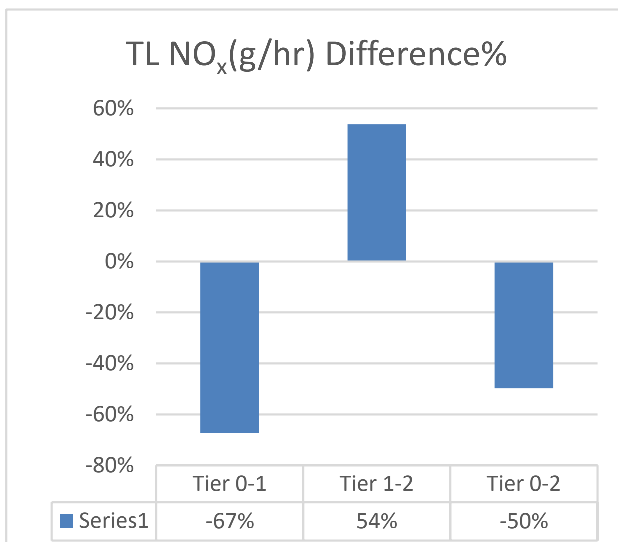
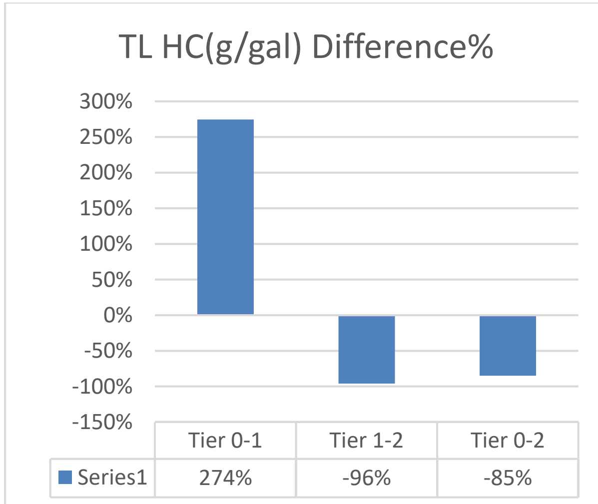
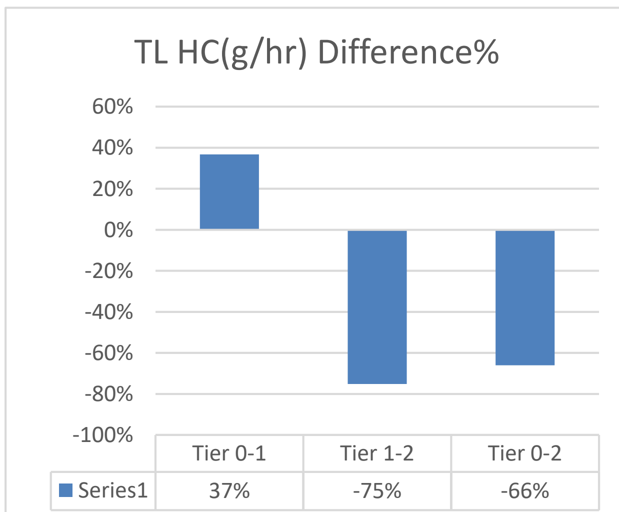


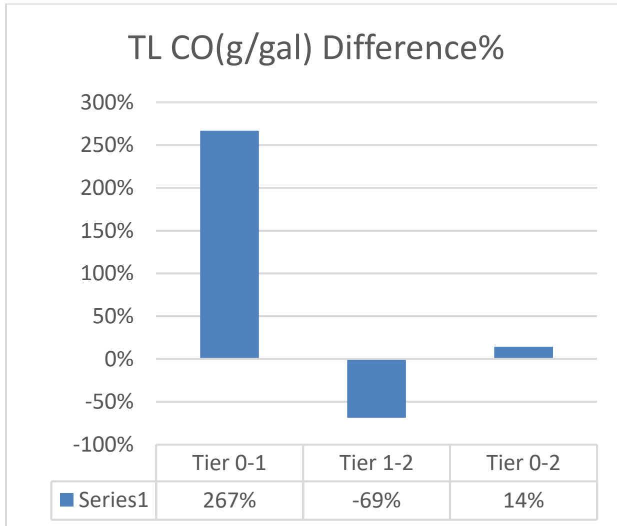
Figure 31. Percentage of Difference in Fuel Use and Emission Rates for Different Tiers of Motor Graders

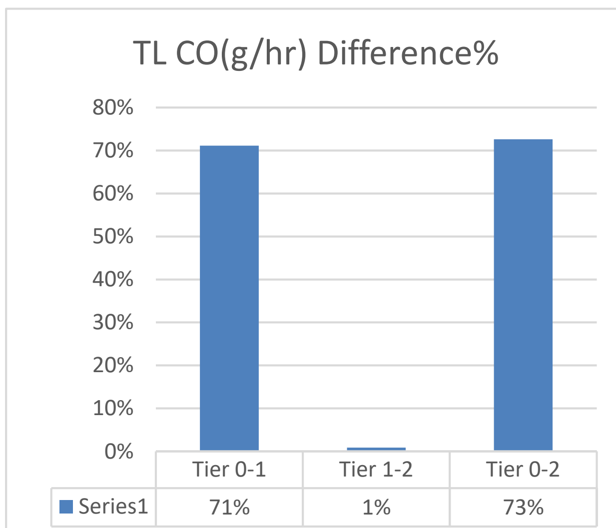

TL NOx(g/gal) Difference%
200%
150%
100%
50%
0%
-50%
-100%
Tier 0-1
Tier 1-2
Tier 2-3
Tier 0-3
Series1
-66%
181%
-62%
-64%

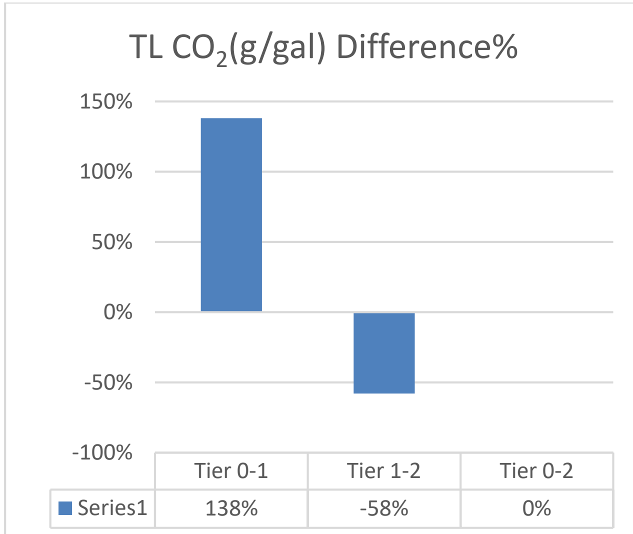

TL NOx(g/hr) Difference%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
-67%
54%
-50%

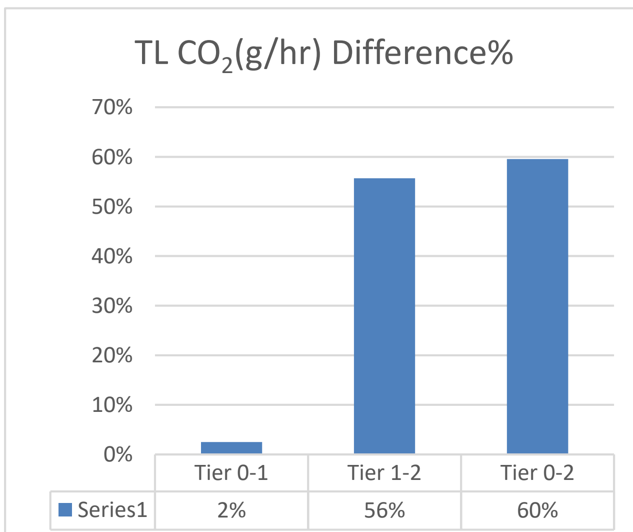

TL HC(g/gal) Difference%
300%
250%
200%
150%
100%
50%
0%
-50%
-100%
-150%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
274%
-96%
-85%

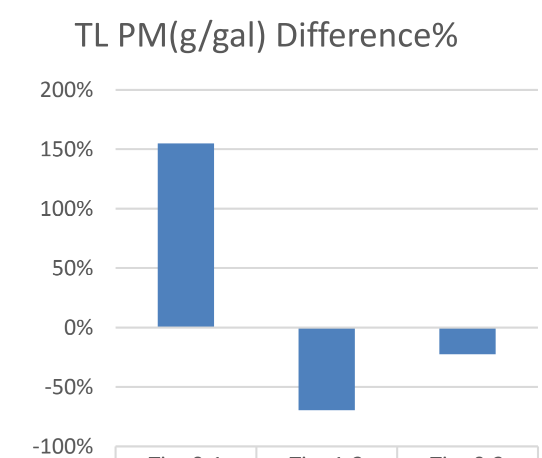

TL HC(g/hr) Difference%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
37%
-75%
-66%


TL CO(g/gal) Difference%
300%
250%
200%
150%
100%
50%
0%
-50%
-100%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
267%
-69%
14%

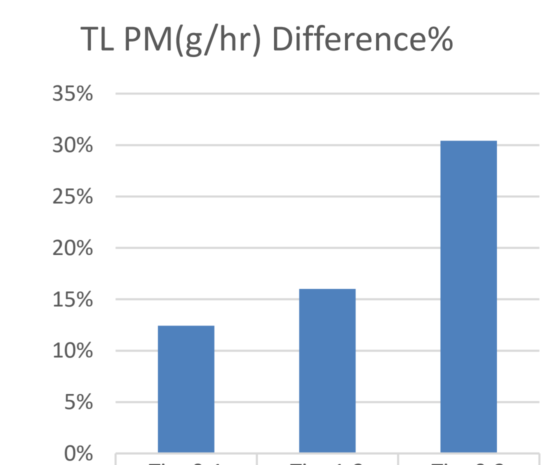

TL CO(g/hr) Difference%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
71%
1%
73%


TL CO2(g/gal) Difference%
150%
100%
50%
0%
-50%
-100%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
138%
-58%
0%


TL CO2(g/hr) Difference%
70%
60%
50%
40%
30%
20%
10%
0%
Tier 0-1
Tier 1-2
Tier 0-2
Series1
2%
56%
60%



	Tier 0-1	Tier 1-2	Tier 0-2
Series1	155%	-70%	-23%



	Tier 0-1	Tier 1-2	Tier 0-2
Series1	12%	16%	30%

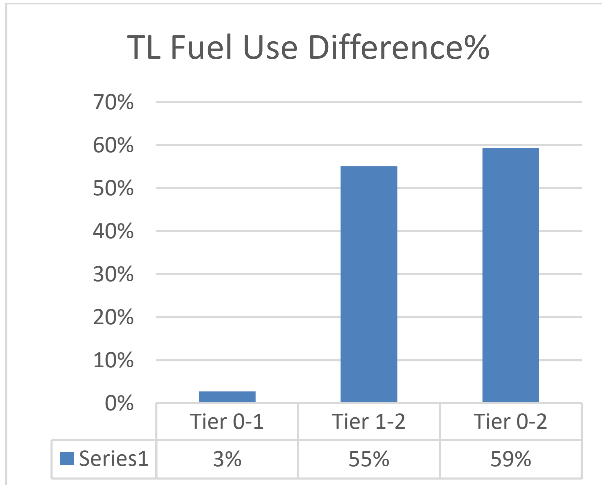


Figure 32. Percentage of Difference in Fuel Use and Emission Rates for Different Tiers of Track Loaders

CHAPTER IV

CONCLUSIONS

The conclusions are divided into three sections that include potential impacts of diesel exhaust on operators; the energy, economic, and environmental impacts of alternative fuels in off-road maintenance equipment; and the energy and environmental impact of engine tier standards (tier 0 vs. tier 1 vs. tier2) in off-road maintenance equipment. Each subsection will be presented as follows.

4.1. Assess Potential Impacts of Diesel Exhaust on Operator

Second-by-second fuel use and emissions data of NO_x, HC, CO, CO_2, and PM as well as engine performance data for each item of equipment while performing their duty-cycle were collected by a group of researchers from North Carolina State University (NCSU). This data provided the basis for our research.

Based on the results in section 3.1.2, tailpipe emissions of NO_x, CO, and CO_2 greatly exceed their respective PEL (or reasonable surrogate). In some cases, the limit was exceeded by orders of magnitude. It is likely that the PEL for Total Dust is frequently exceeded since tailpipe emissions of diesel particulate matter alone sometimes exceed the limit. Although it is reasonable to assume that concentrations of these tailpipe exhaust pollutants will be diluted in outdoor air before entering the equipment cab, it is also reasonable to assume that at least some of these pollutants will enter into the cab (given its close proximity to the tailpipe) and result in poor IAQ for the operator. What must be determined is how much pollutants enter the cab and what their impacts are.

It is also apparent that there is a relationship between engine activity parameters, such as RPM and MAP, and tailpipe exhaust pollutants. Based on the results, there was a positive relationship between RPM, MAP, and each of the measured tailpipe pollutant emissions. Identifying and characterizing these relationships are critical. By determining the impact of equipment operation on the emission of pollutants, it is possible to identify technological and operational strategies that reduce the operator's exposure to these hazardous pollutants while also improving IAQ inside the equipment cab. Furthermore, additional analysis will help answer a more fundamental question – Is an enclosed cab better or worse than a non-enclosed cab for equipment operators?

4.2. Assess the Energy, Economical, and Environment Impacts of Alternative Fuels

Based on the results in section 3.2.2, the major conclusion is that there are measurable differences in the economic, energy, and environmental impacts of B20 compared to petroleum diesel when used in off road maintenance equipment. B20 had a higher average price per gallon, as well as a higher average hourly fuel use rate than petroleum diesel; however, B20 had lower average emissions of NO_x, HC, CO, and CO_2 on a gram per gallon basis. Average grams per gallon emissions of PM for B20 were slightly higher than petroleum diesel. Using petroleum diesel as a baseline, B20 had a slightly negative impact with regard to economics (based on cost) and energy (based on fuel consumption); however, B20 had an overall positive environmental impact with respect to pollutant emissions.

4.3. Assess the Energy and Environmental Impact of Engine Tier Standards (Tier 0 vs. Tier 1 vs. Tier2)

Based on the results, the major conclusion is that there are measurable differences in the impacts of higher tier number when used in off road maintenance equipment. Overall, we can see improvement regarding emission rates in more than 60% of cases, when we go to higher tier number. Fuel use decreases as well in almost all cases with higher tier number. Therefore, the general conclusion is that higher tier number has a positive environmental impact based on reductions in emissions of NO_x, HC, CO, and CO_2 on a gram per gallon and gram per hour basis as well as fuel use on a gram per hour basis.

CHAPTER V

RECOMMENDATIONS

Assuming that further analysis of existing data yields similar results that show tailpipe emissions of NO_x, CO, and CO_2 greatly exceed their respective PEL (or reasonable surrogate), the next step is to acquire pollutant concentration measurements inside the cabs of in-use heavy equipment. Pollutant concentration measurements may be taken by using IAQ meters that are commonly used for building science analyses. Most IAQ meters are small and durable enough to reside inside the cab of heavy equipment without interfering with the operator's performance and without sustaining damage. These meters are capable of measuring real-time concentrations of NO_2, CO, CO_2, and Total Suspended Particles (TSP) at specified time intervals. This type of data will definitively show whether or not permissible exposure limits of these pollutants are exceeded inside the cab, and if so, the frequency and duration of the overexposure.

In order to totally characterize IAQ in heavy equipment cabs, the pollutant concentration data from inside the cab should be analyzed in tandem with the corresponding tailpipe pollutant emissions data on a real-time basis. This investigation would require a portable emissions measurement system to collect the tailpipe emissions data while simultaneously using an IAQ meter to collect pollutant concentration measurements inside the cab. These two sets of data would then be synchronized to provide a complete picture of what is happening inside of and outside of the equipment cab with regard to pollutant emissions. This type of study will enable researchers to characterize IAQ in heavy equipment cabs at its primary source – the tailpipe – and ultimately provide pollution mitigation strategies that improve IAQ inside equipment cabs.

Biofuels are known as environmentally friendly products for years, so we comparatively analyzed the economic, energy, and environmental impacts of biodiesel versus petroleum diesel in off-road maintenance equipment to decide whether or not to use biodiesel instead of petroleum diesel in maintenance equipment. In addition to the economic, energy, and environmental impacts, there are other issues to consider as well. These issues include switching costs, engine maintenance, and equipment productivity.

Fleet managers should consider the costs associated with switching from petroleum diesel to biodiesel. In most cases, these costs are small or even negligible since the fundamental design of diesel engines allows either fuel to be used. Depending on the chemical properties of the biodiesel used, some engine components made of nitrile rubber compounds – such as hoses, gaskets, plastics, and seals – can be susceptible to degradation; therefore, these items may break down and need replacement more frequently than similar items used with petroleum diesel ("Growing the Demand for Biofuels in Off-highway Equipment Applications",2015). Although these components are relatively inexpensive compared to other engine parts, more frequent replacement may lead to higher long-term maintenance costs.

Maintenance considerations include the impact of biodiesel on the engine itself. When compared to petroleum diesel, biodiesel provides improved lubricity that may extend engine component life; however, biodiesel is also more prone to sticking on the engine cylinder walls and blowing past the piston rings into the crankcase, although oil dilution has not been reported as a major concern. Some equipment fleets reported problems with fuel filter plugging after initially switching from petroleum diesel to biodiesel, especially when B20 or higher blends were used. Furthermore, in winter seasons, some fleets located in colder regions reportedly had to switch back to petroleum diesel since biodiesel has a higher cloud and pour point, causing it to gel at a higher temperature than petroleum diesel ("Growing the Demand for Biofuels in Off-highway Equipment Applications",2015). Fleet managers should carefully consider engine maintenance issues when deciding whether or not to use biodiesel in their equipment.

Equipment productivity is based on how efficiently the engine can transfer power into work. Although B20 and lower blends typically do not show a noticeable loss in power in real-world conditions, any loss in power will be more appreciable in equipment that operates at consistently high engine loads, such as motor graders and wheel loaders ("Growing the Demand for Biofuels in Off-highway Equipment Applications",2015). Furthermore, B20 has about 2% less energy content than petroleum diesel and therefore lower fuel economy, which means that more than one gallon of biodiesel is consumed in order to produce the same amount of work that one gallon of petroleum diesel produces. Likewise, the total fuel costs and total emissions for the activity will increase because more fuel is consumed. Fleet managers should consider the impacts on equipment productivity and the resulting economic, energy, and environmental impacts when deciding whether or not to use biodiesel in their equipment.

Future study can consider switching cost from petroleum diesel to biodiesel; maintenance cost, equipment productivity, and energy content of biodiesel in order to investigate fuel cost and emissions when biodiesel is being used in the equipment.

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APPENDICES

The appendices provide supporting data, results, or calculation used as part of overall results.

The appendices are divided into several appendixes as follows:

- **Appendix A-** Time series data for pollutants and engine activities for Wheel Loader 1 through Wheel Loader 5
- **Appendix B-** 2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Fuel Uses
- **Appendix C-** 2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Backhoe's Pollutants
- **Appendix D-** 2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Motor Grader's Pollutants
- **Appendix E-** 2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Wheel Loader's Pollutants
- **Appendix F-** Cumulative Frequency Diagram (CFD) of Each Pollutant on a Gram per Hour Basis
- **Appendix G-** One-Way ANOVA-Tukey Test Results for Dozers
- **Appendix H-** One-Way ANOVA-Tukey Test Results for Motor Graders
- **Appendix I-** One-Way ANOVA-Tukey Test Results for Track Loaders
- **Appendix J-** Summary of Equipment Attributes

Appendix A

Time series data for pollutants and engine activities for Wheel Loader 1 through Wheel Loader 5

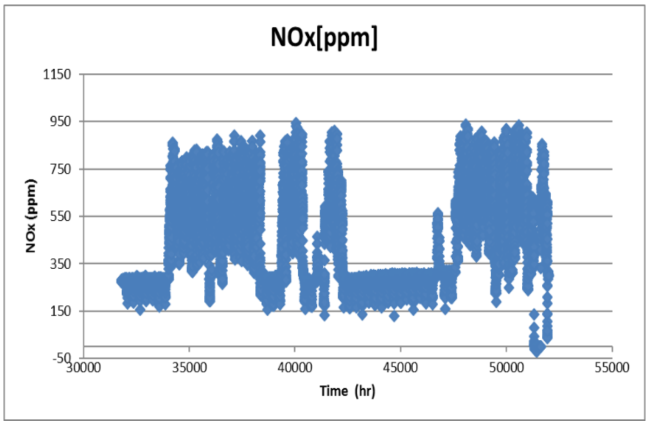


Figure A.1. NO_x versus Time for WL2

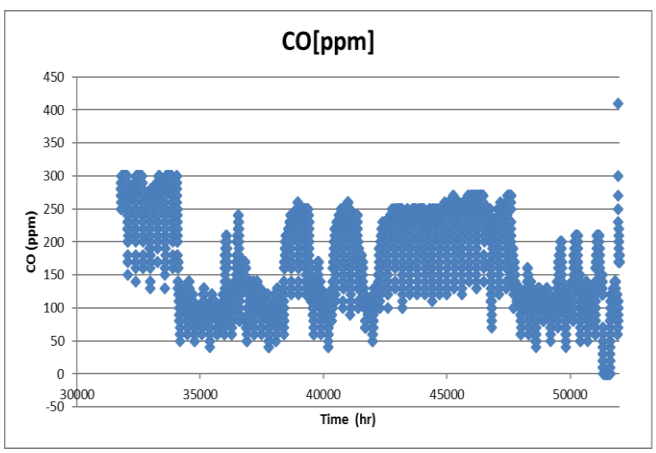


Figure A.2. CO versus Time for WL2

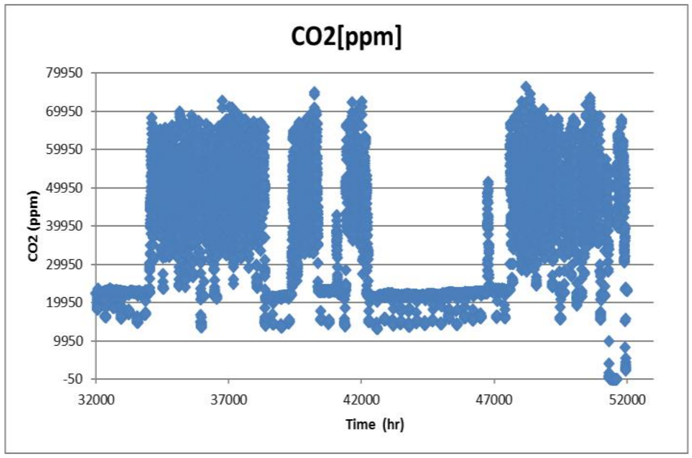


Figure A.3. CO_2 versus Time for WL2

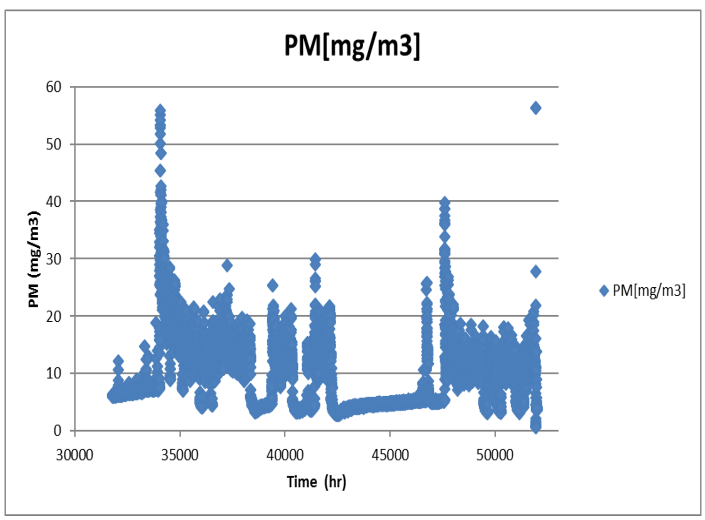


Figure A.4. PM versus Time for WL2

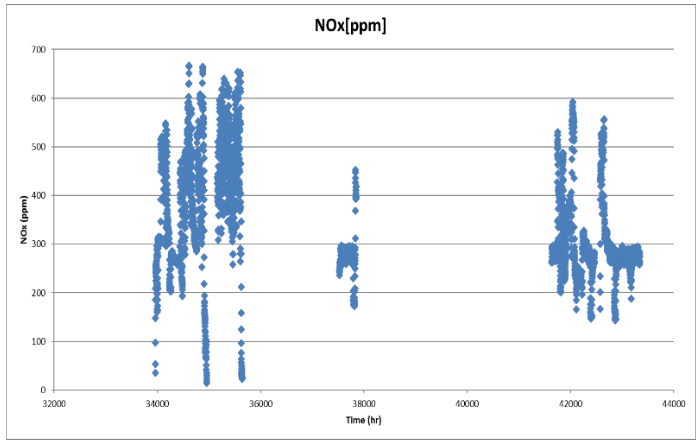


Figure A.5. NO_x versus Time for WL3

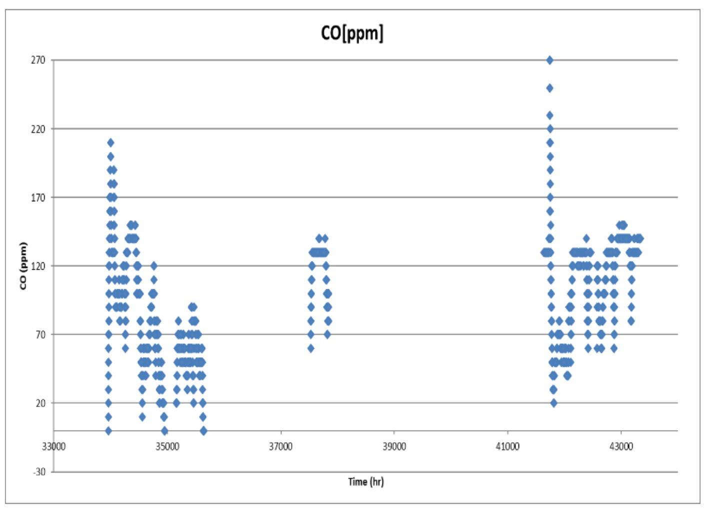


Figure A.6. CO versus Time for WL3

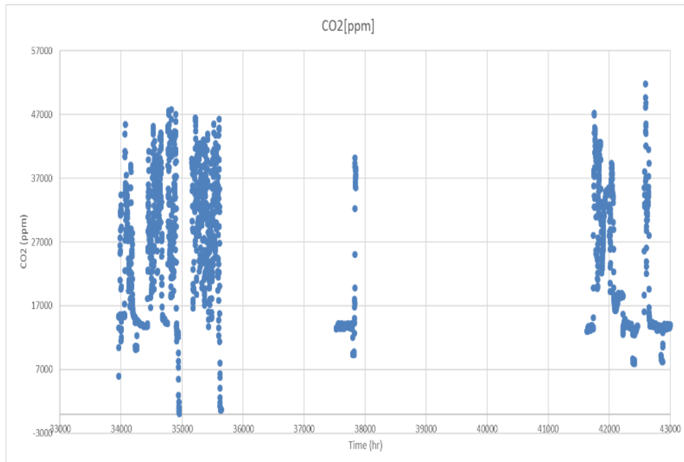


Figure A.7. CO_2 versus Time for WL3

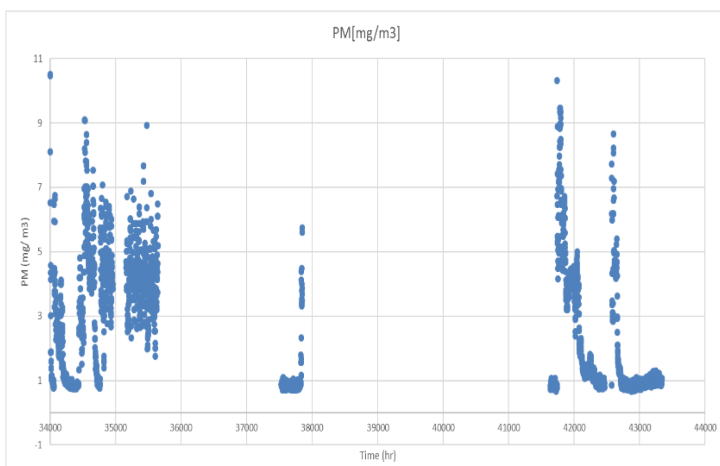


Figure A.8. PM versus Time for WL3

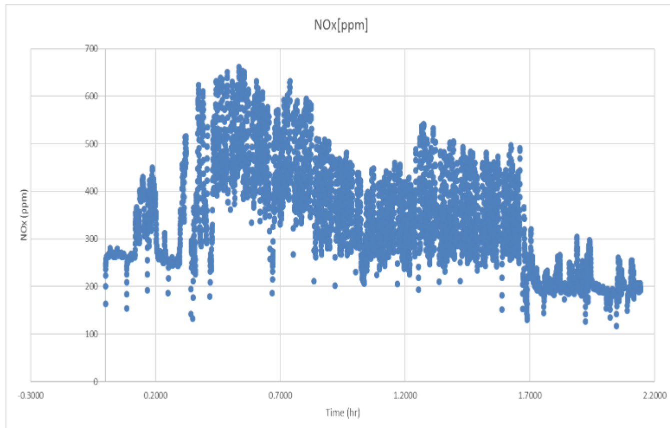


Figure A.9. NO_x versus Time for WL4

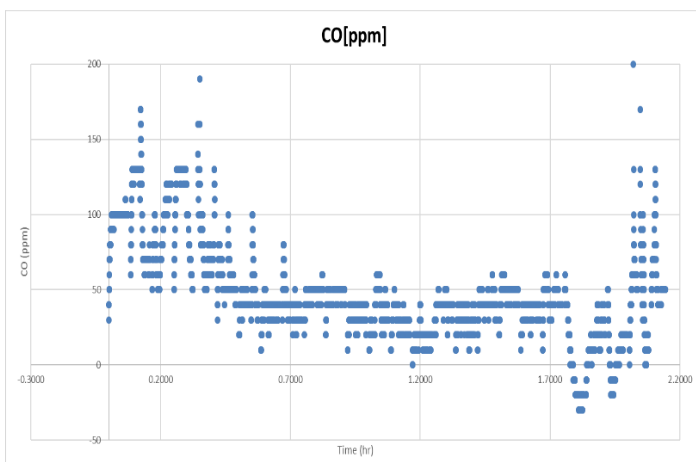


Figure A.10. CO versus Time for WL4

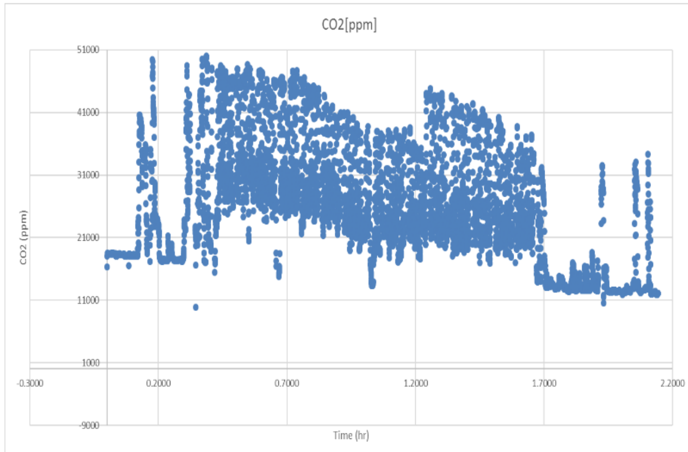


Figure A.11. CO_2 versus Time for WL4

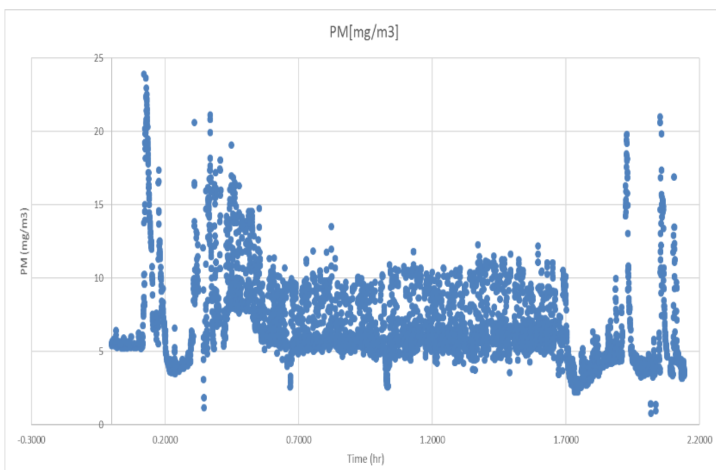


Figure A.12. PM versus Time for WL4

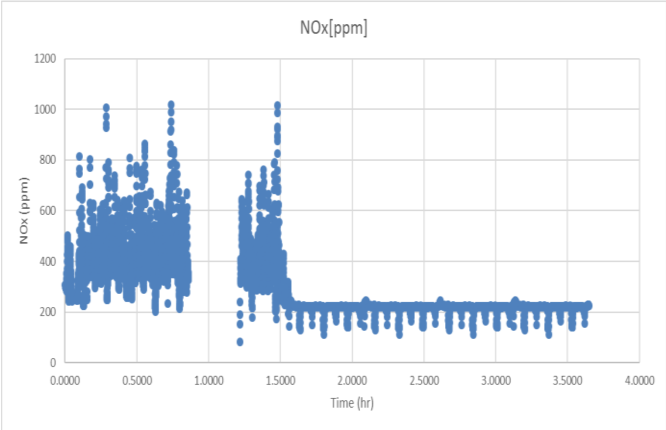


Figure A.13. NO_x versus Time for WL5

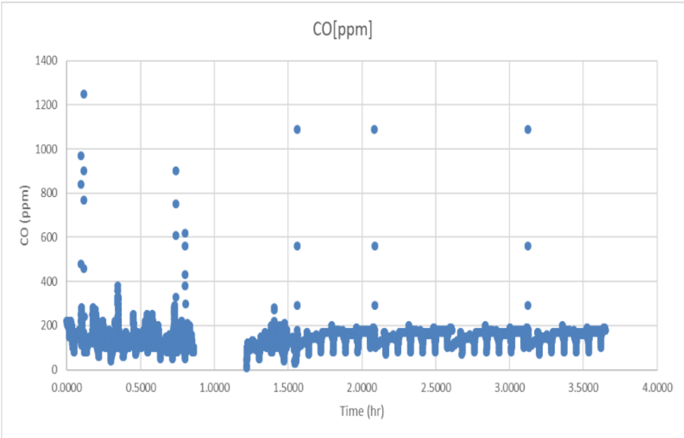


Figure A.14. CO versus Time for WL5

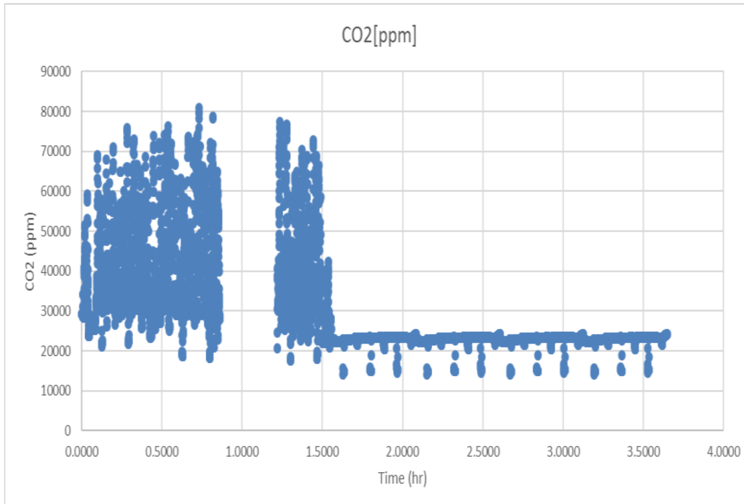


Figure A.15. CO_2 versus Time for WL5

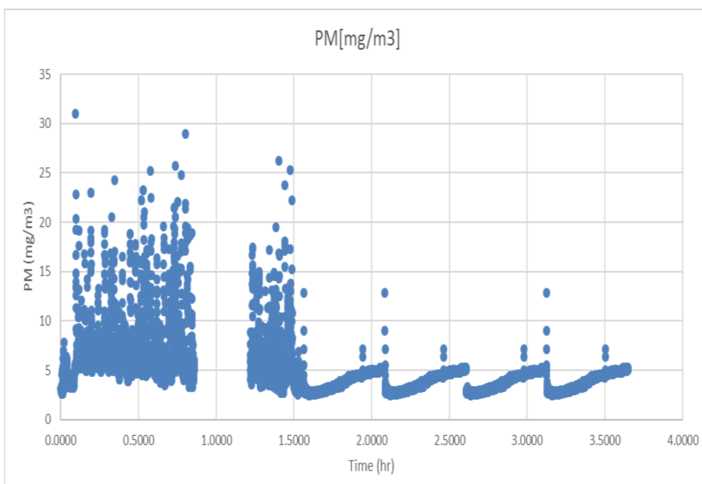


Figure A.16. PM versus Time for WL5

Appendix B

2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Fuel Uses

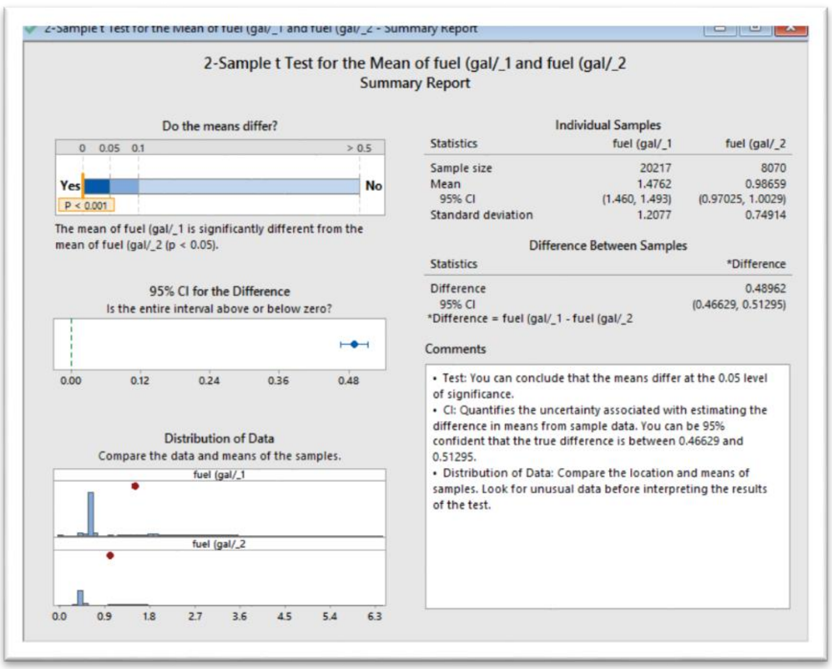


Figure B.1. 2 Sample t-Test for the Mean of Fuel Use for Wheel Loader 2

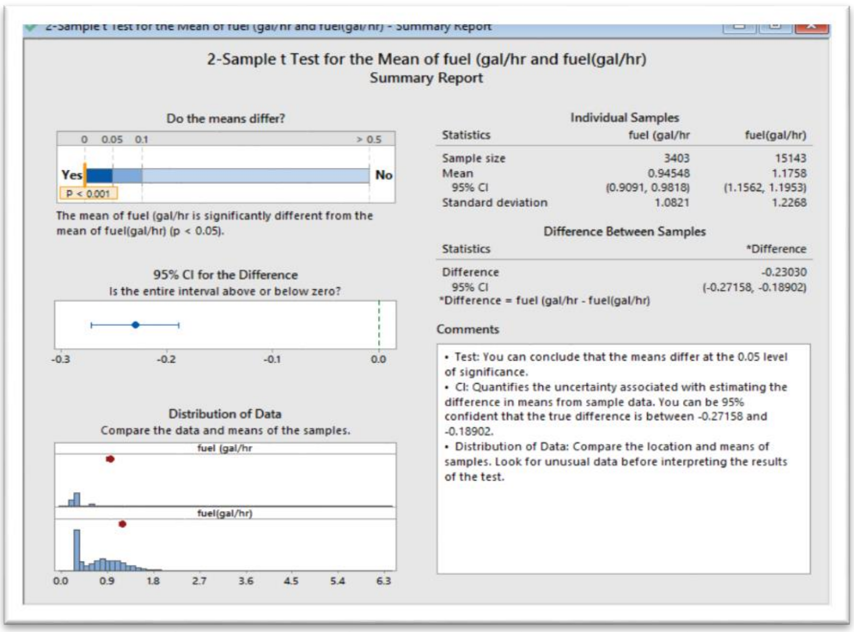


Figure B.2. 2 Sample t-Test for the Mean of Fuel Use for Wheel Loader 3

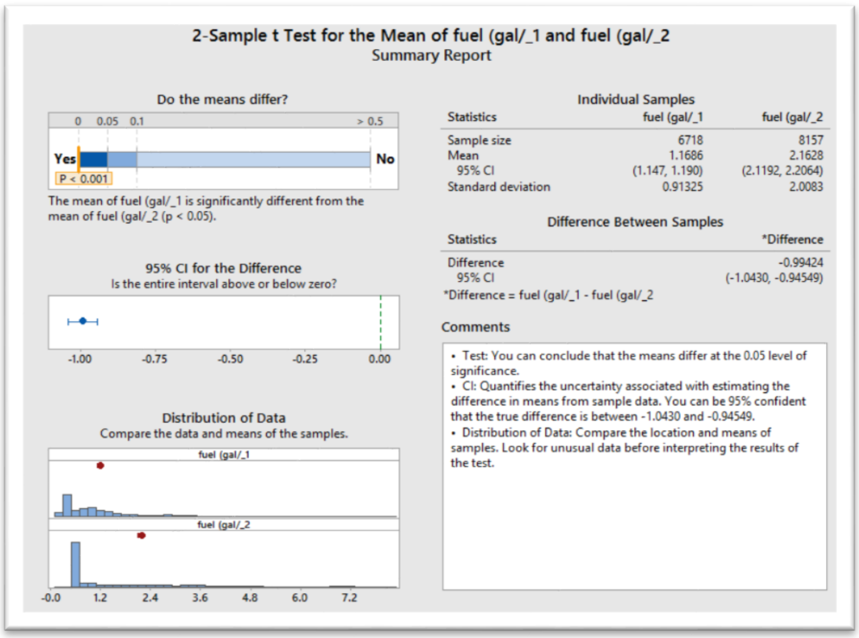


Figure B.3. 2 Sample t-Test for the Mean of Fuel Use for Wheel Loader 4

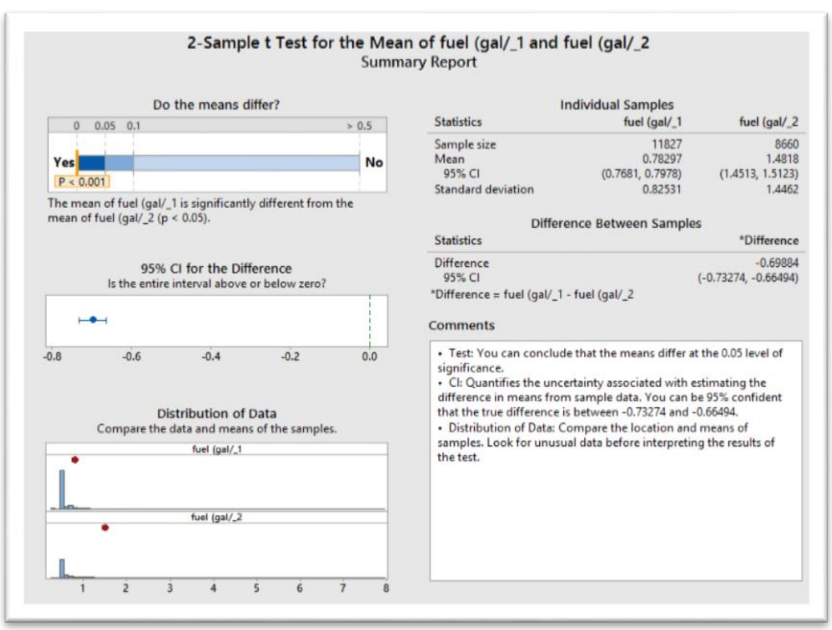


Figure B.4. 2 Sample t-Test for the Mean of Fuel Use for Wheel Loader 5

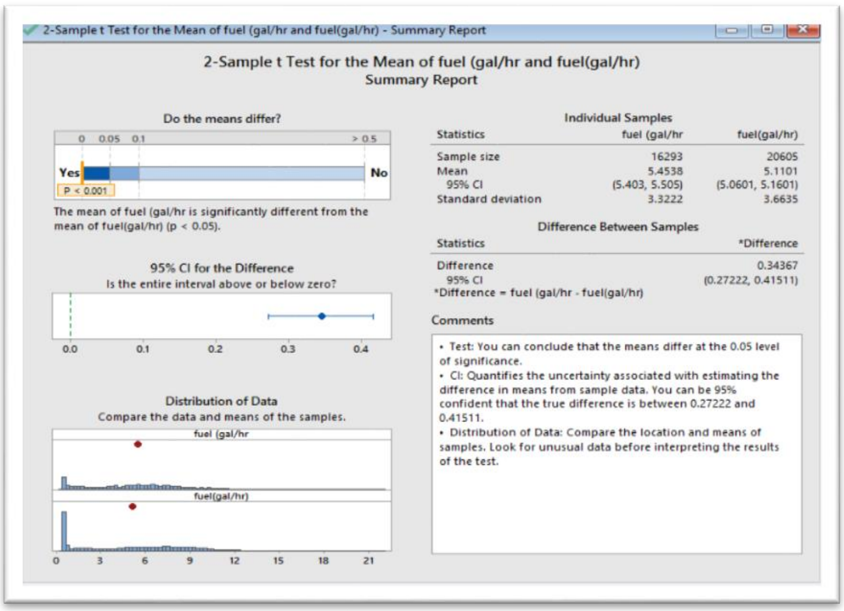


Figure B.5. 2 Sample t-Test for the Mean of Fuel Use for Motor Grader 1

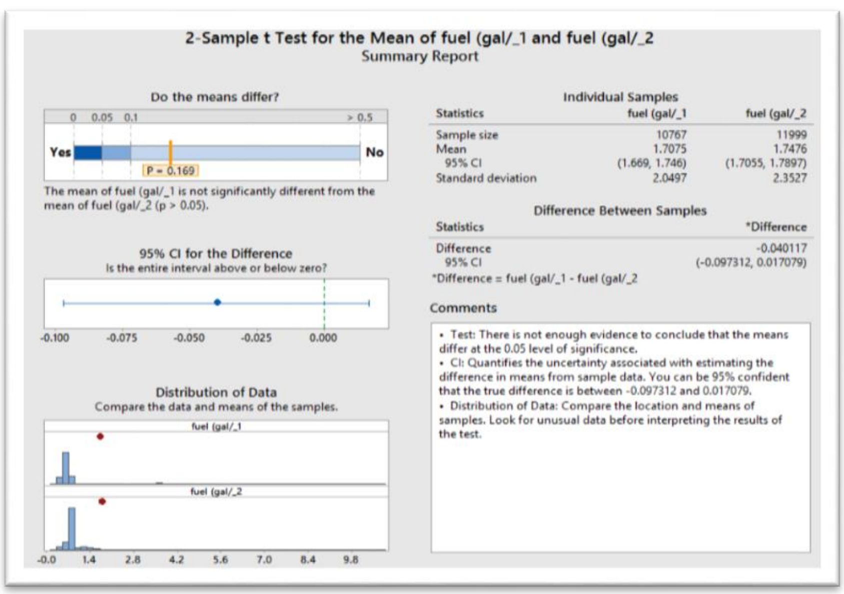


Figure B.6. 2 Sample t-Test for the Mean of Fuel Use for Motor Grader 2

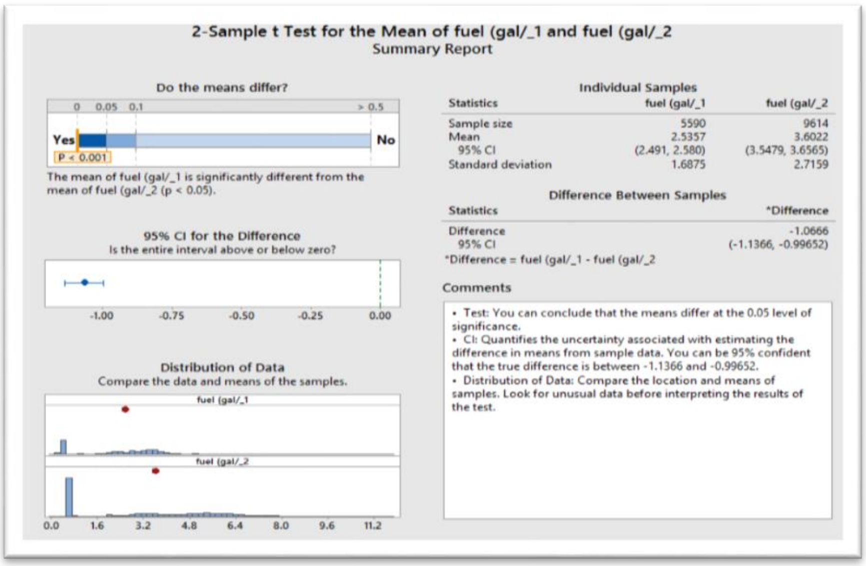


Figure B.7. 2 Sample t-Test for the Mean of Fuel Use for Motor Grader 3

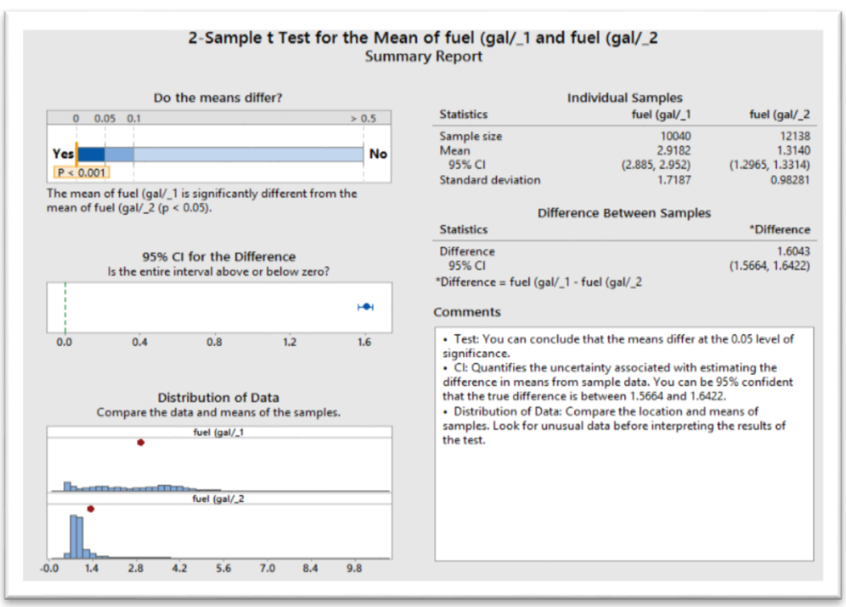


Figure B.8. 2 Sample t-Test for the Mean of Fuel Use for Motor Grader 4

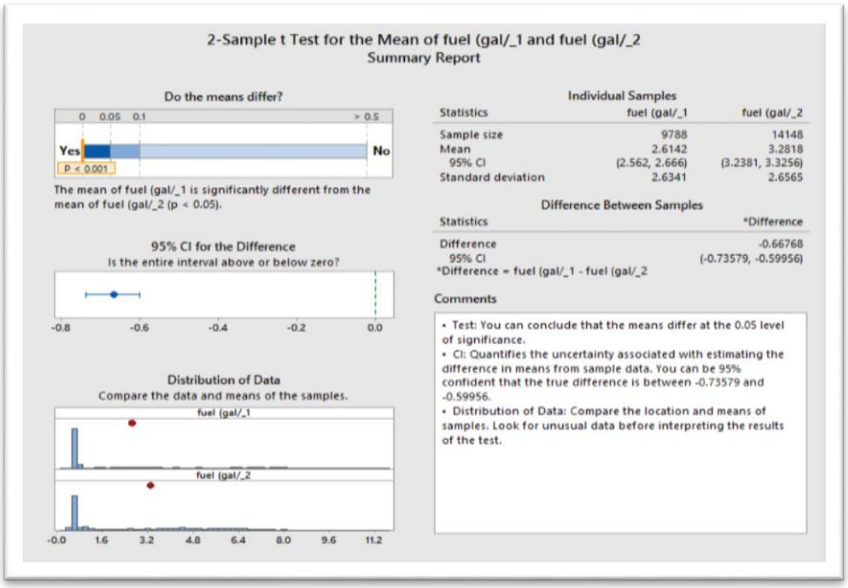


Figure B.9. 2 Sample t-Test for the Mean of Fuel Use for Motor Grader 5

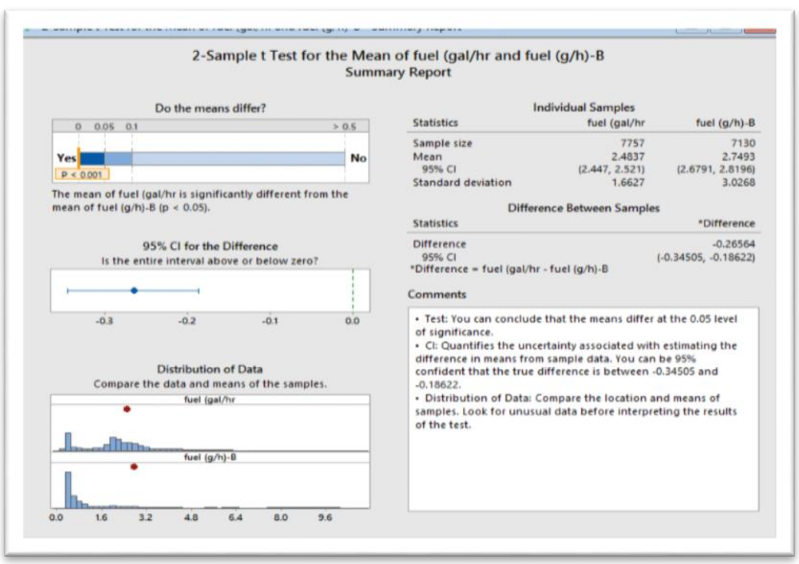


Figure B.10. 2 Sample t-Test for the Mean of Fuel Use for Motor Grader 6

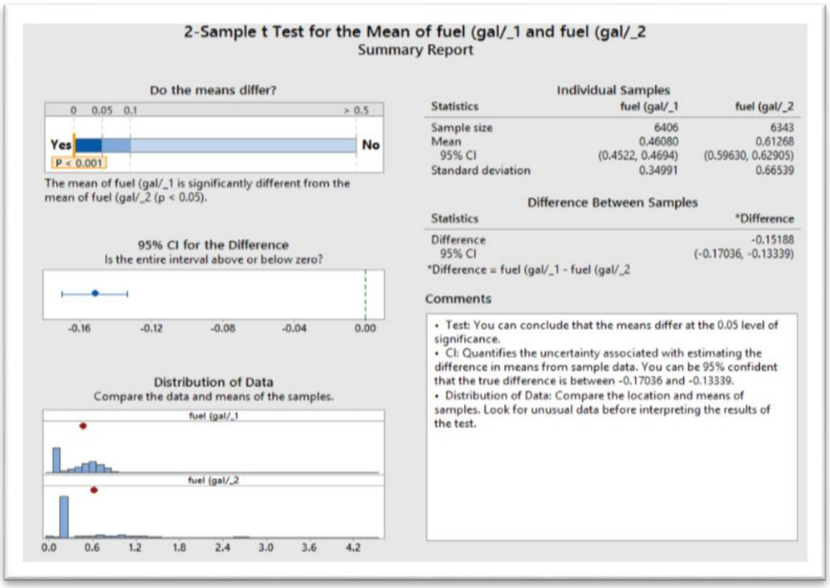


Figure B.11. 2 Sample t-Test for the Mean of Fuel Use for Backhoe 4

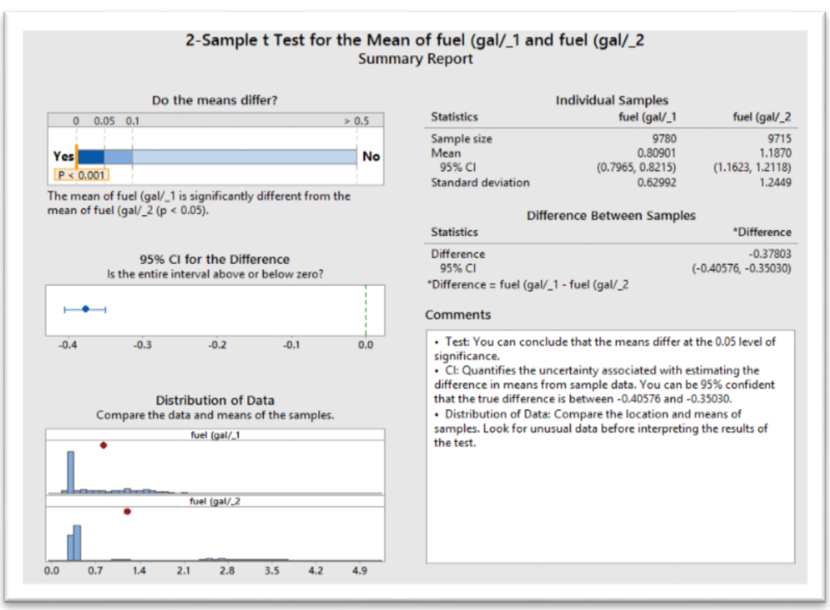


Figure B.12. 2 Sample t-Test for the Mean of Fuel Use for Backhoe 7

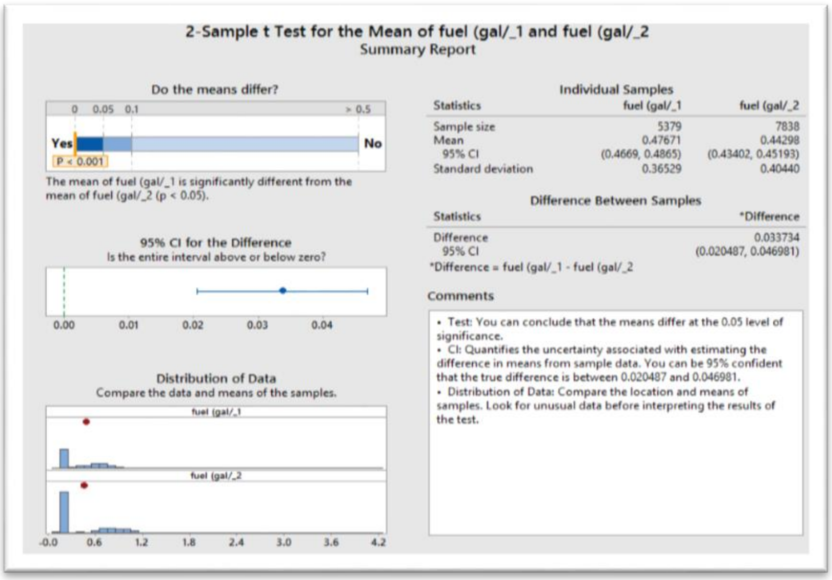


Figure B.13. 2 Sample t-Test for the Mean of Fuel Use for Backhoe 8

Appendix C

2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Backhoe's Pollutants

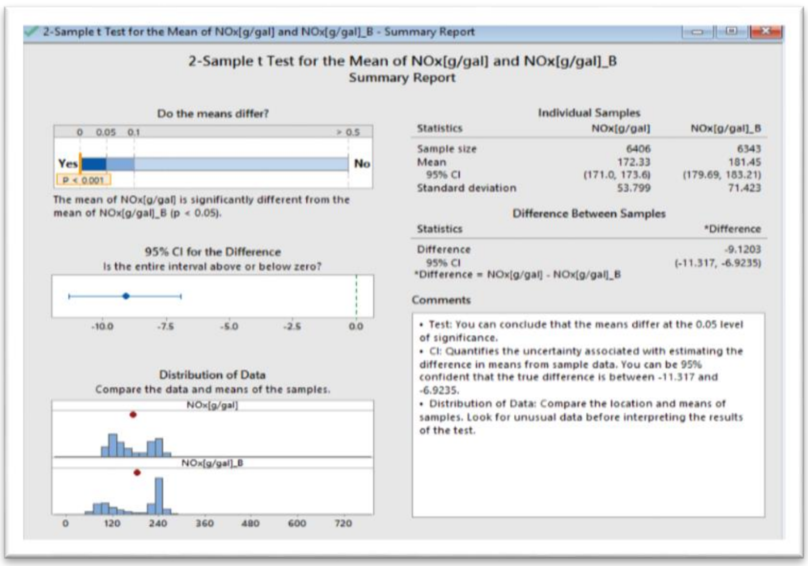


Fig C.1. 2 Sample t-Test for the Mean of No_x (g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 1

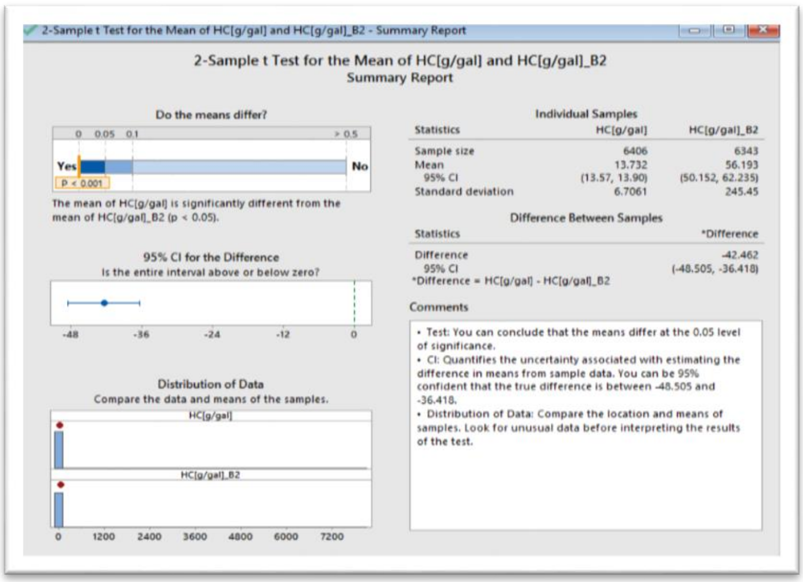


Fig C.2. 2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 1

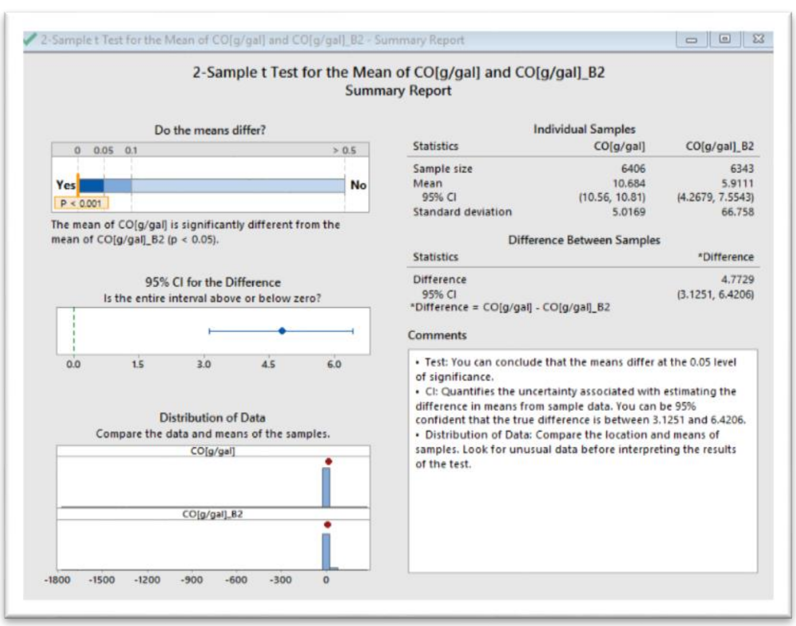


Fig C.3. 2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 1

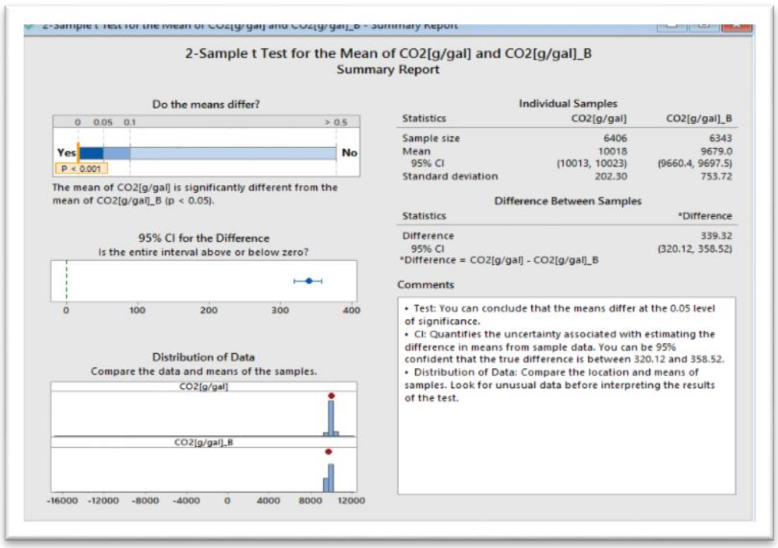


Fig C.4. 2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 1

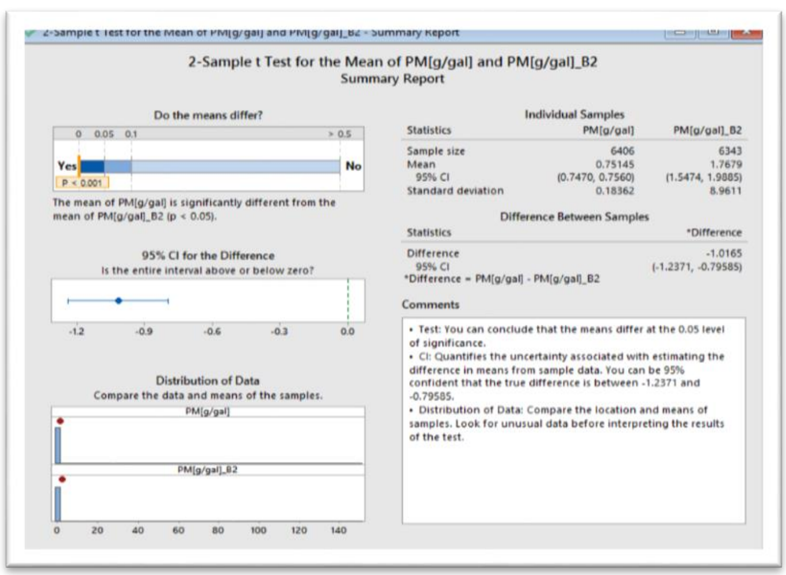


Fig C.5. 2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 1

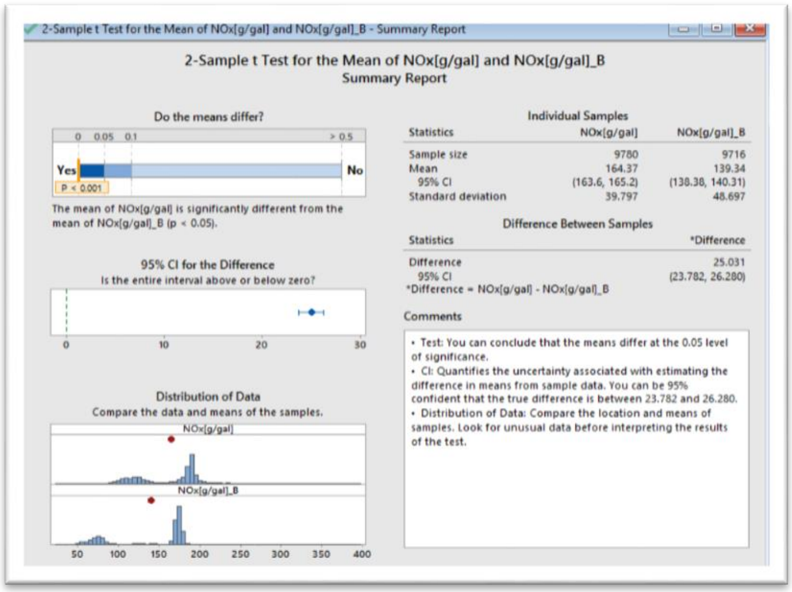


Fig C.6. 2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 2

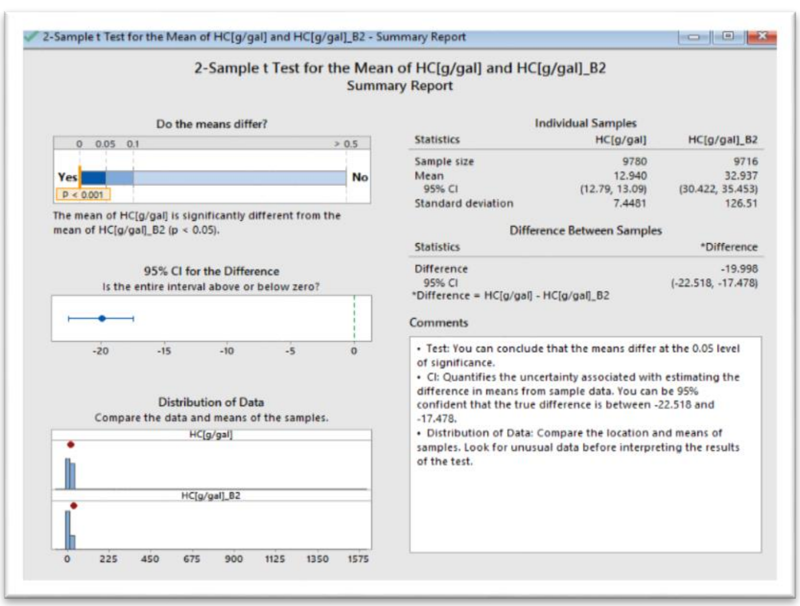


Fig C.7. 2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 2

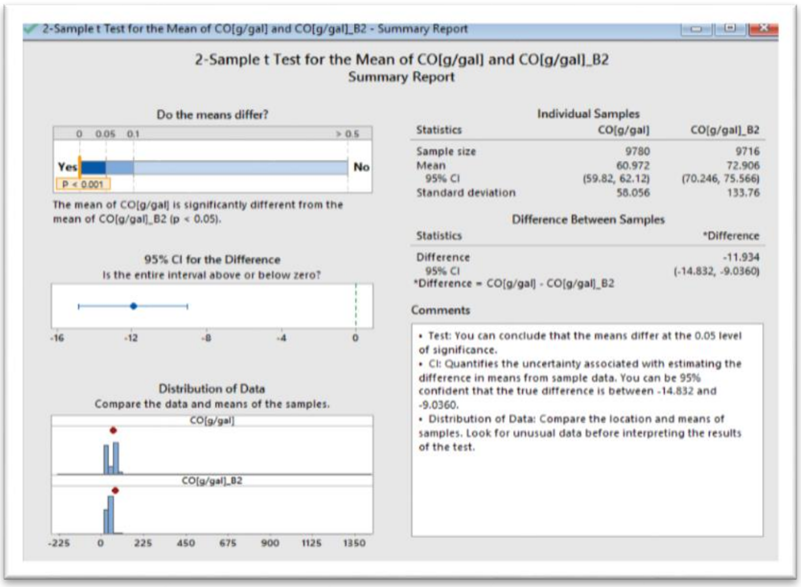


Fig C.8. 2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 2

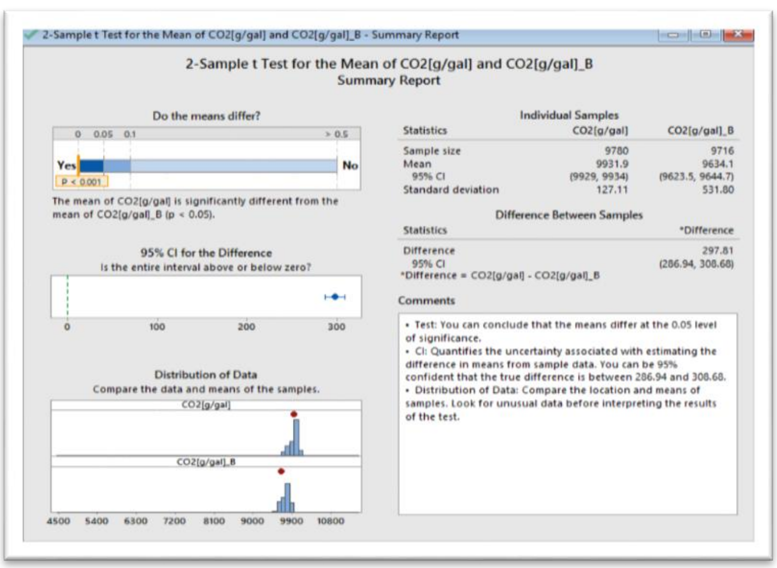


Fig C.9. 2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 2

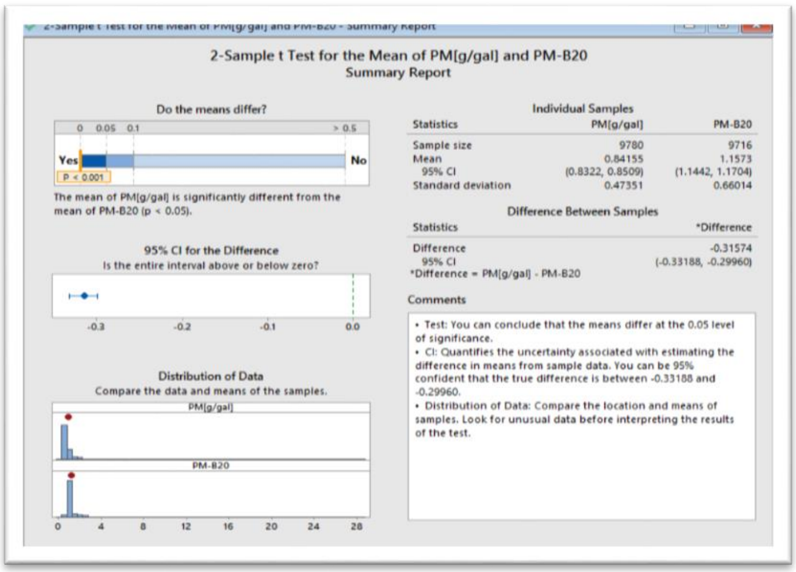


Fig C.10. 2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 2

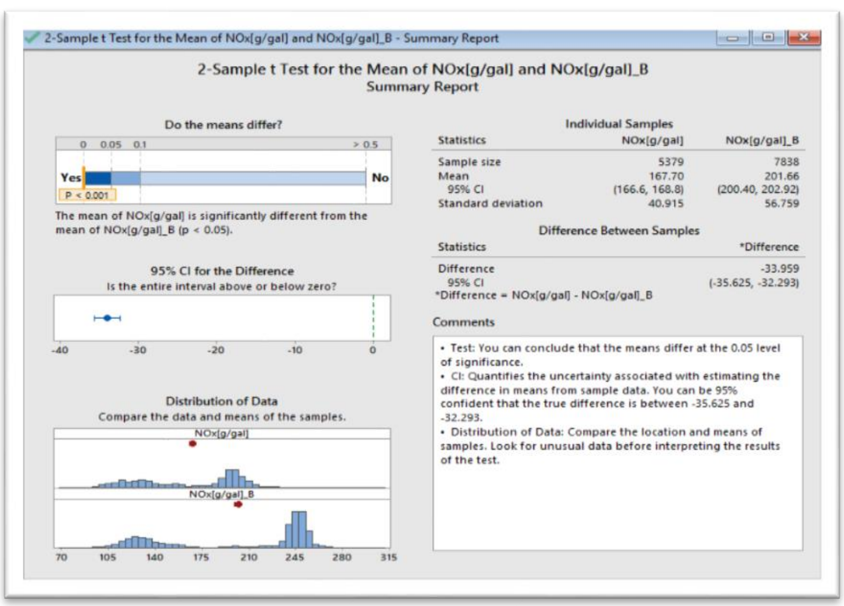


Fig C.11. 2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 3

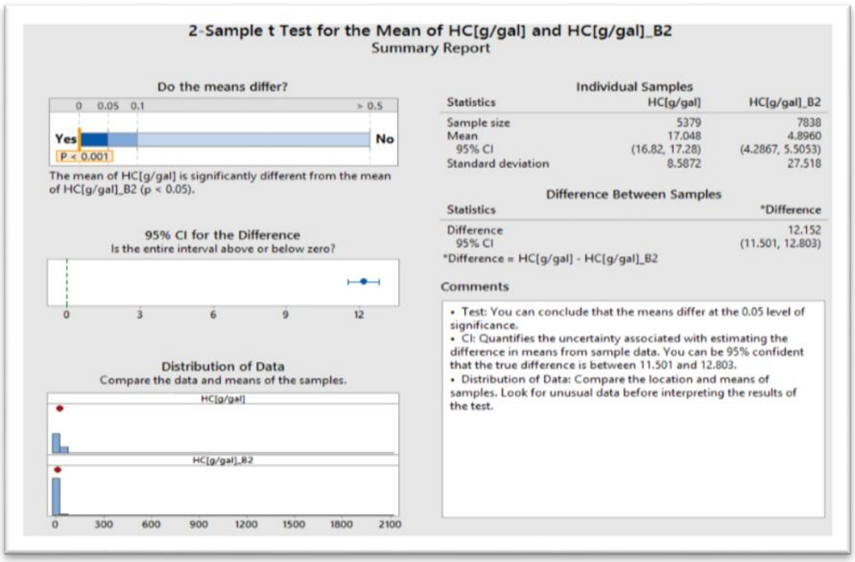


Fig C.12. 2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 3

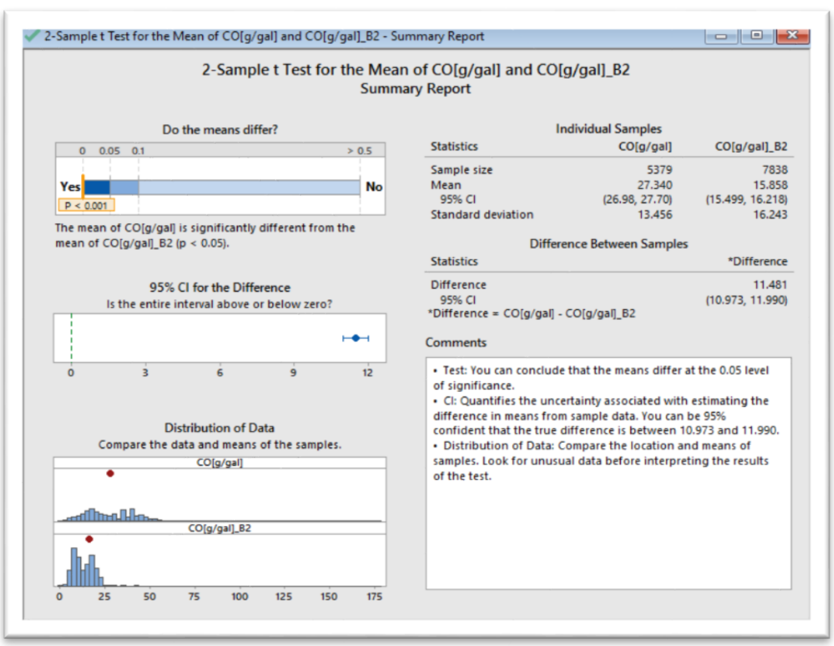


Fig C.13. 2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 3

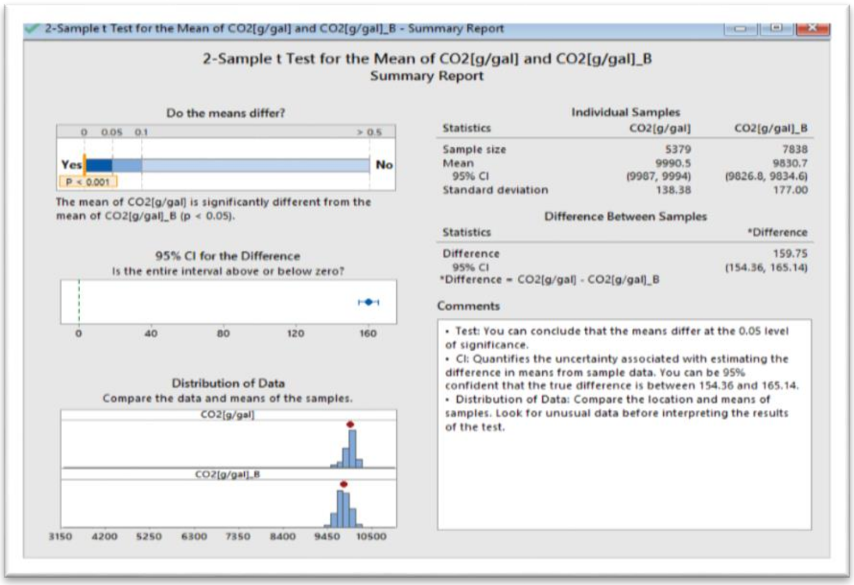


Fig C.14. 2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 3

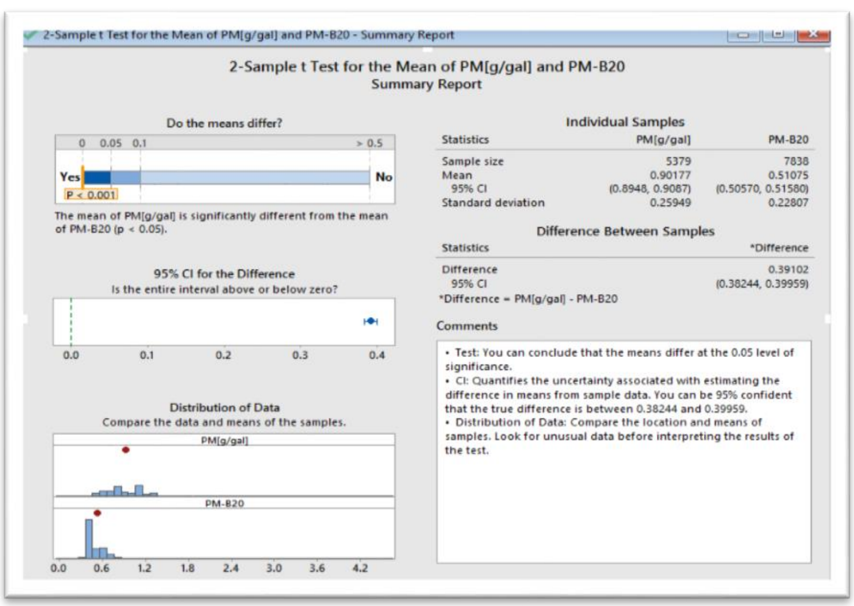


Fig C.15. 2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Backhoe 3

Appendix D

2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Motor Grader's Pollutants

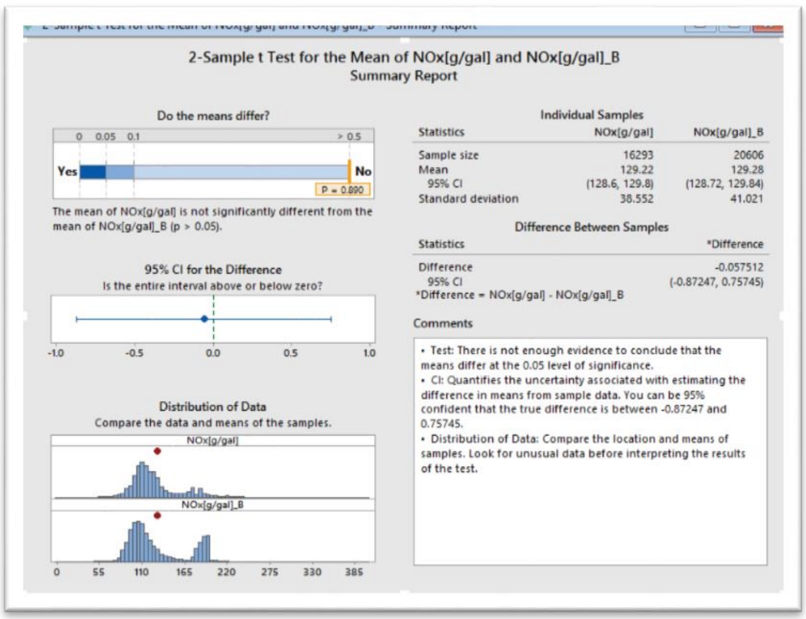


Fig D.1.2 Sample t-Test for the Mean of No_x(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

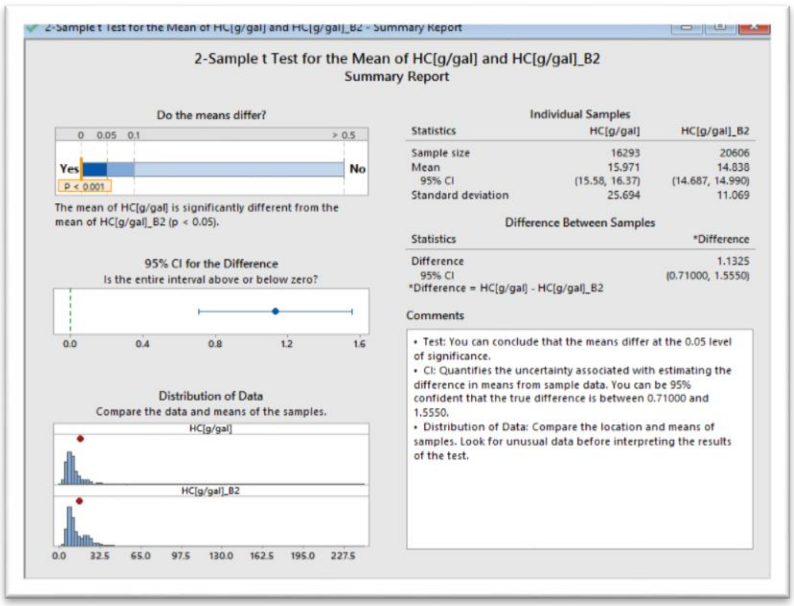


Fig D.2.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

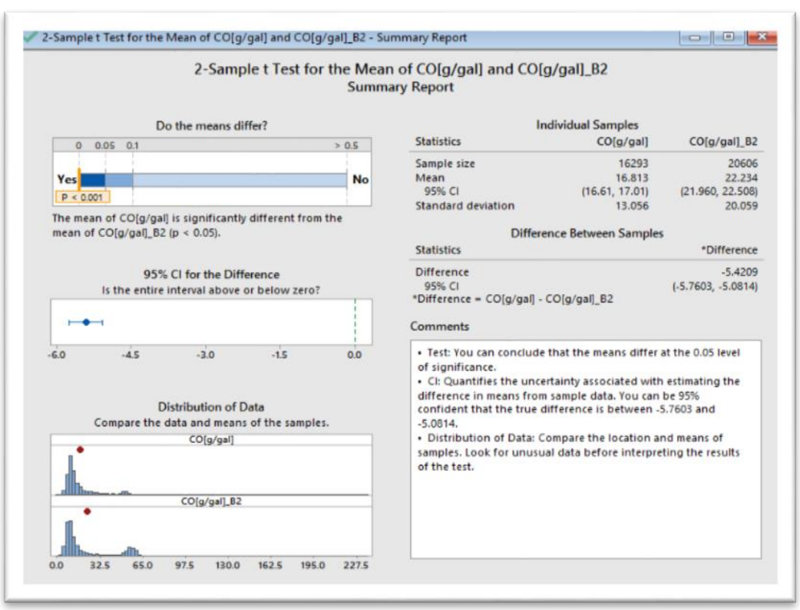


Fig D.3.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

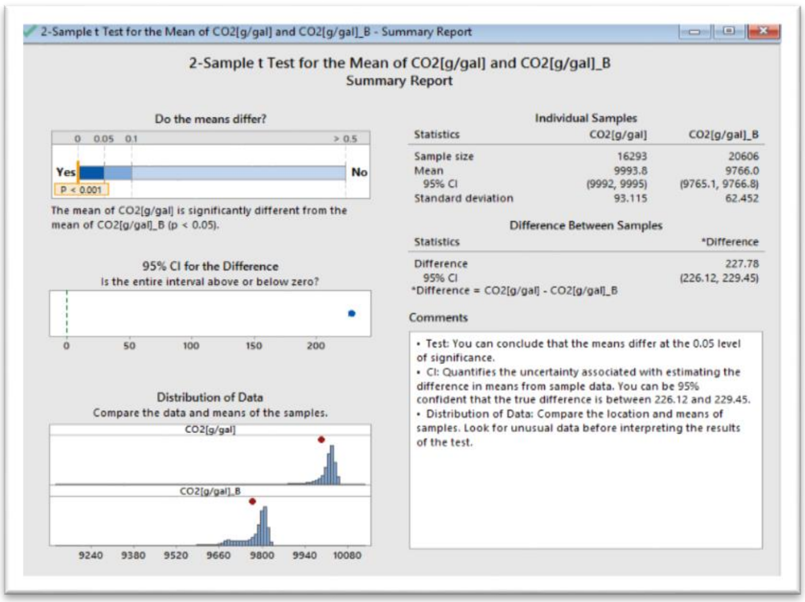


Fig D.4.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

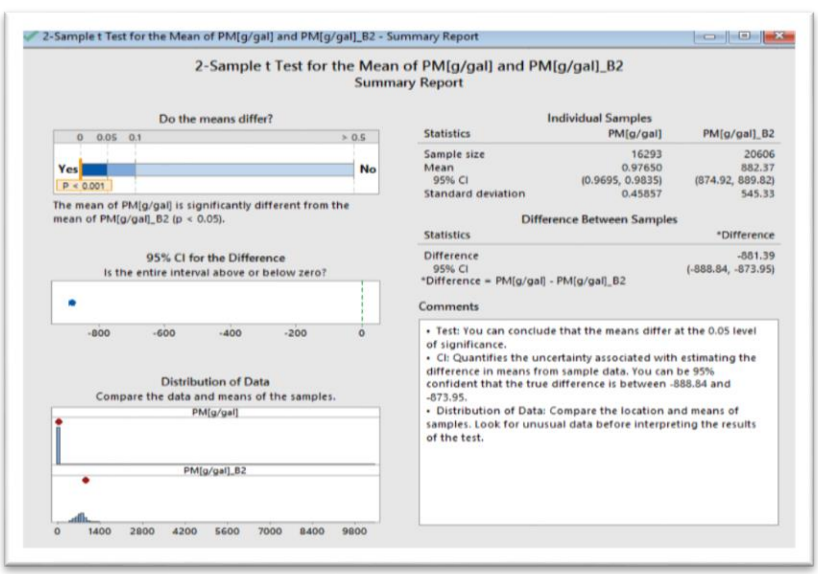


Fig D.5.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

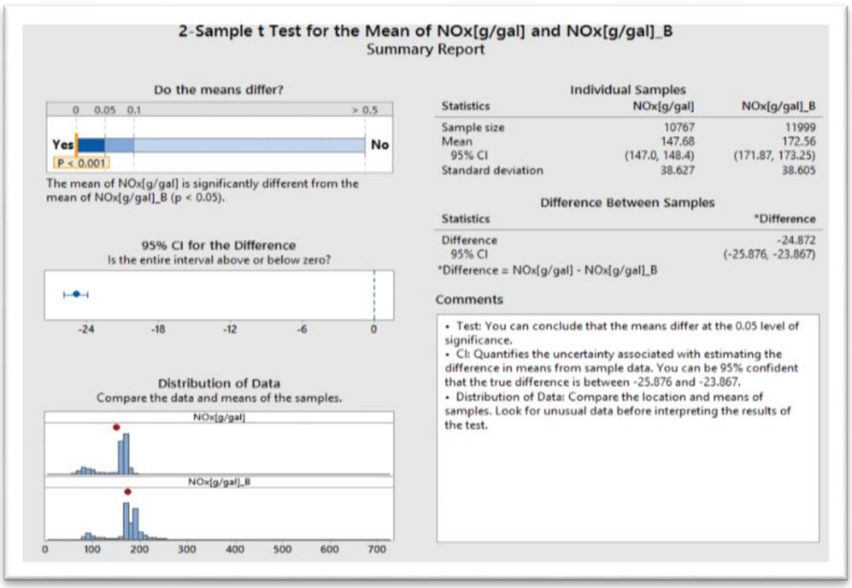


Fig D.6.2 Sample t-Test for the Mean of No_x(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

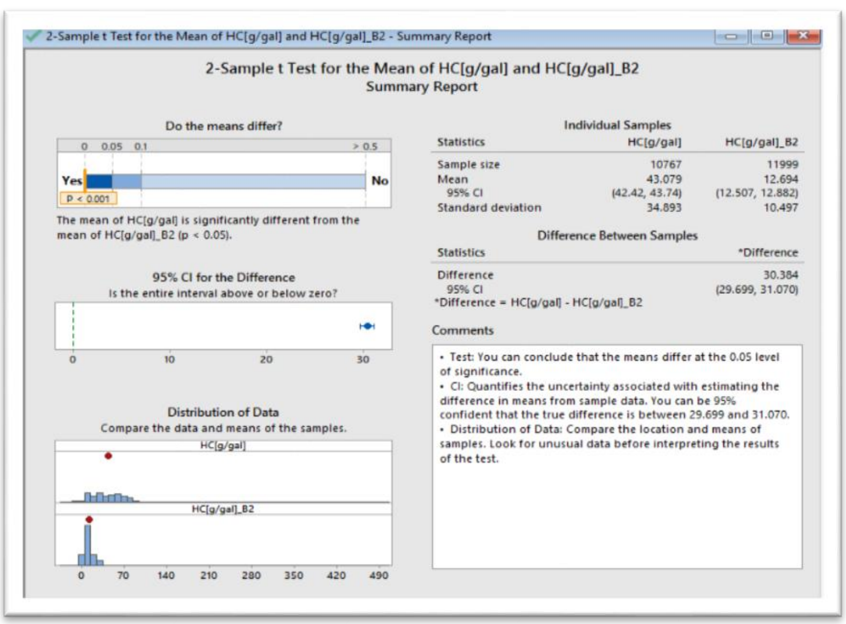


Fig D.7.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

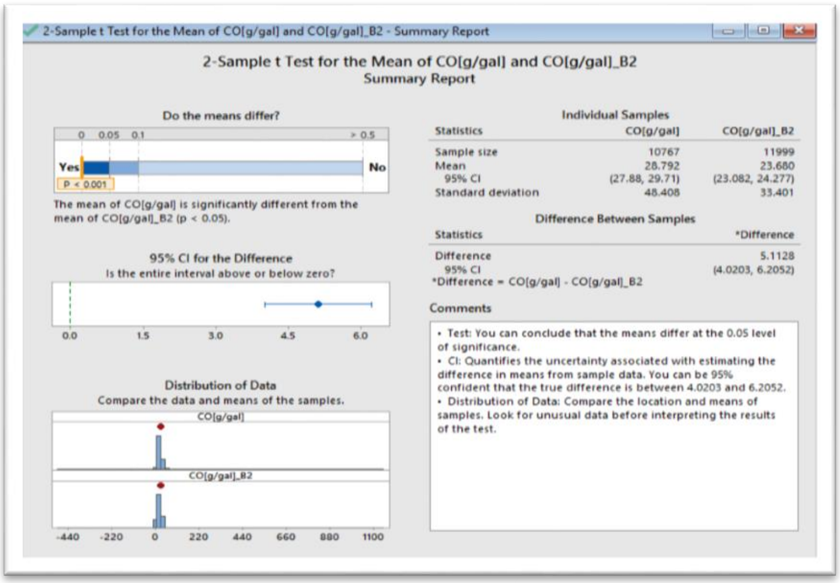


Fig D.8.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

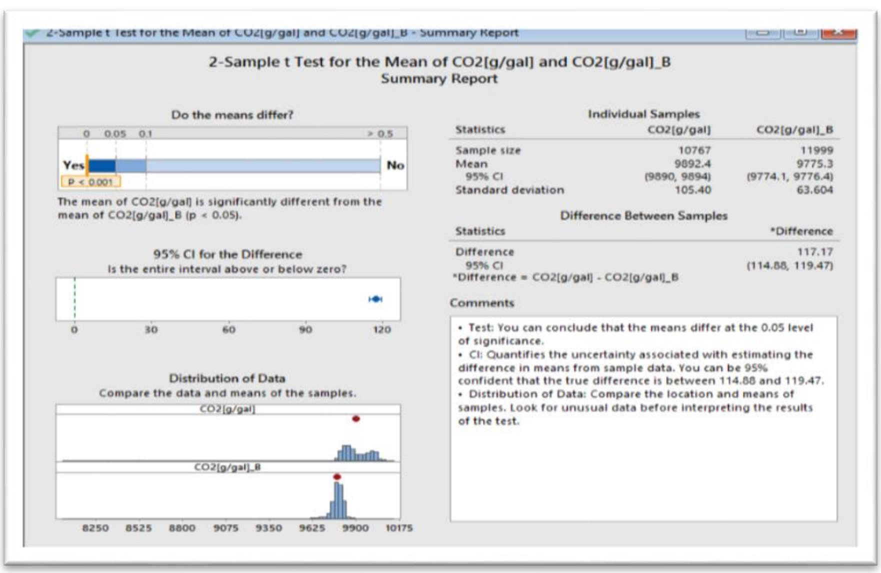


Fig D.9.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

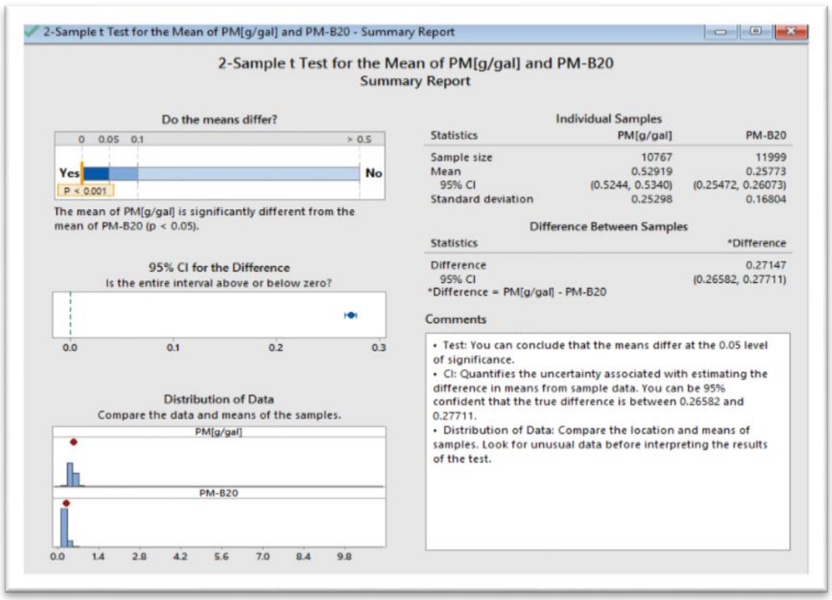


Fig D.10.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader1

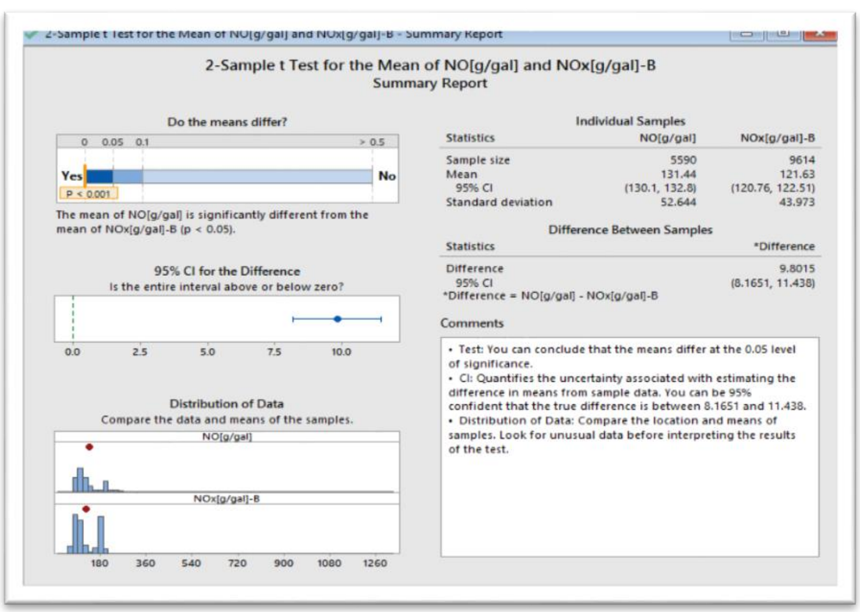


Fig D.11.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader2

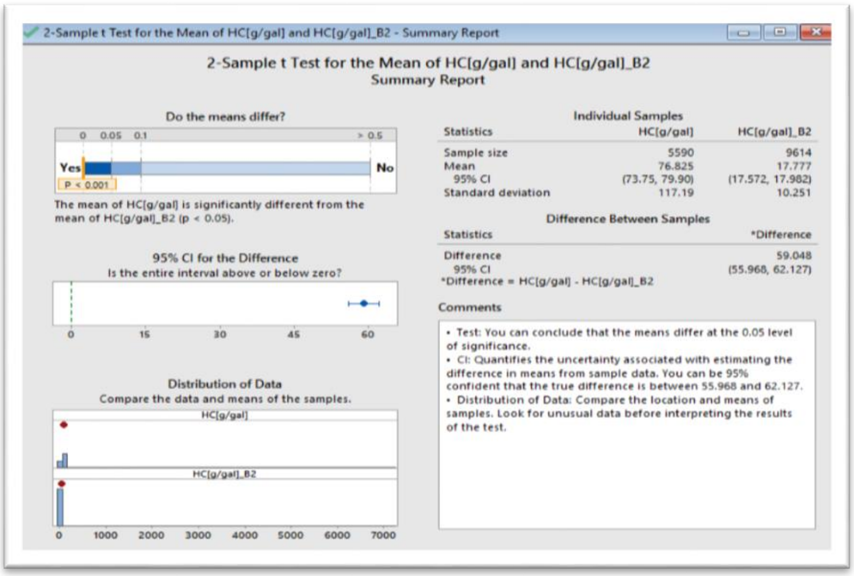


Fig D.12.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader2

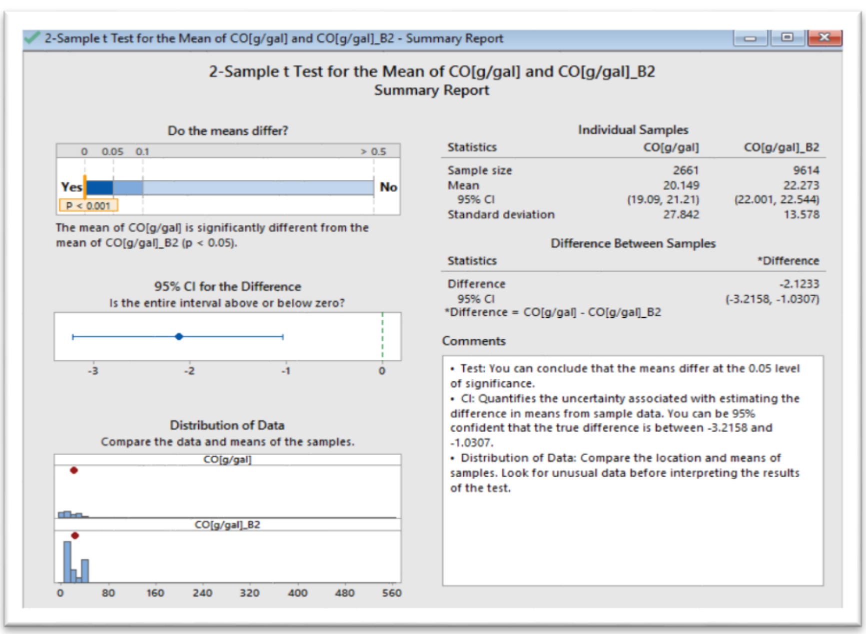


Fig D.13.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader2

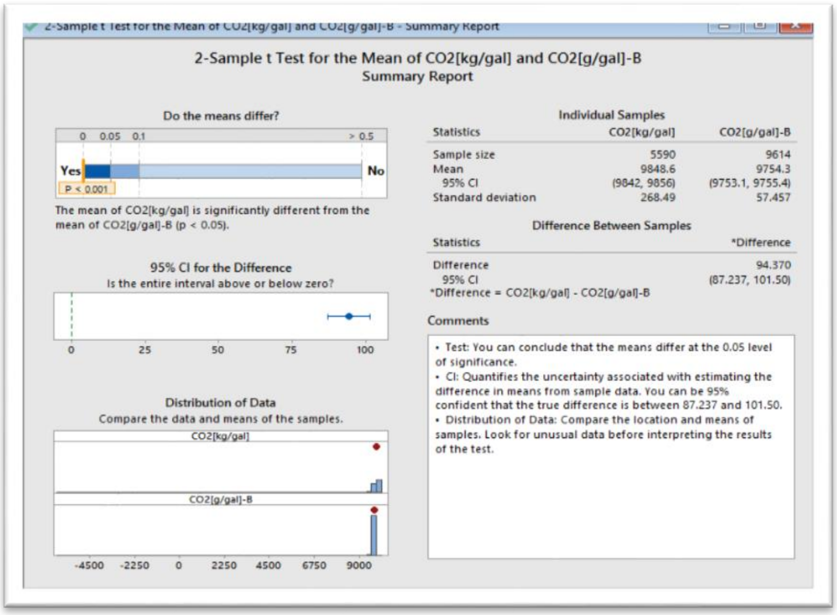


Fig D.14.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader2

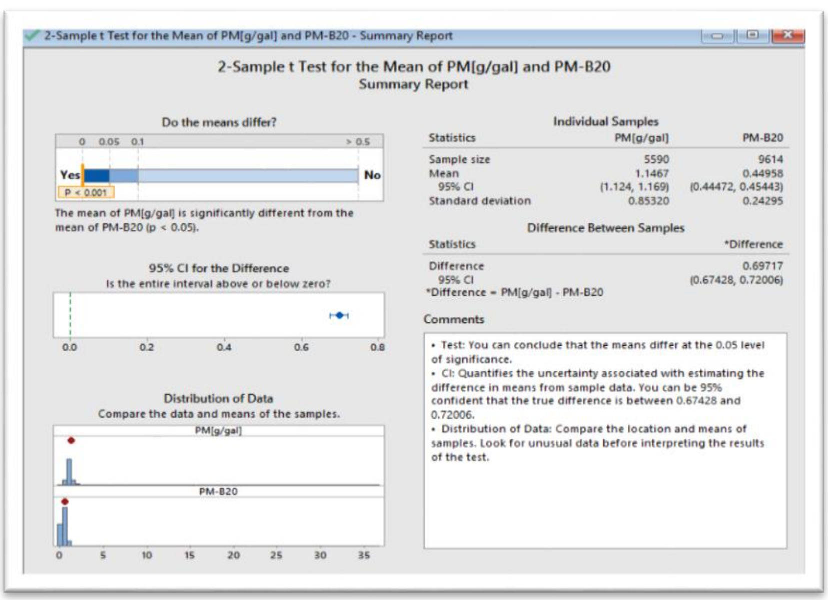


Fig D.15.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader2

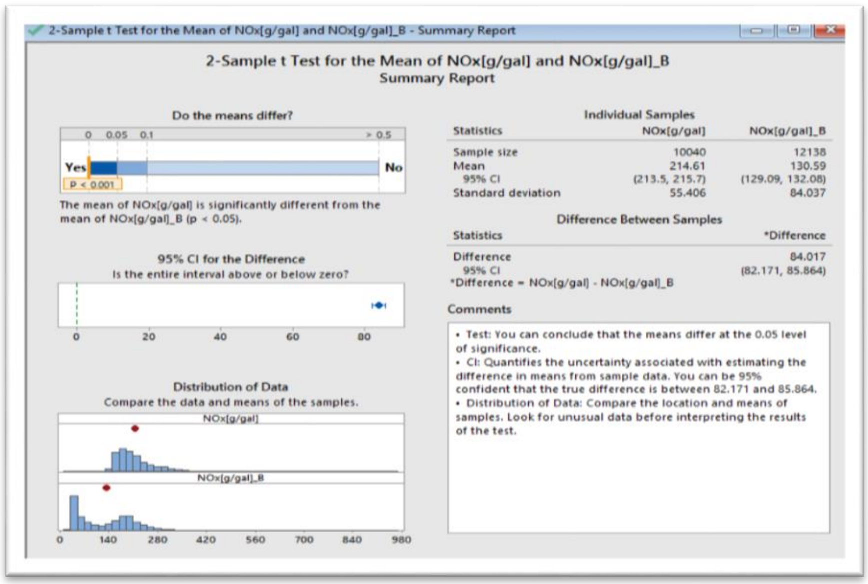


Fig D.16.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader3

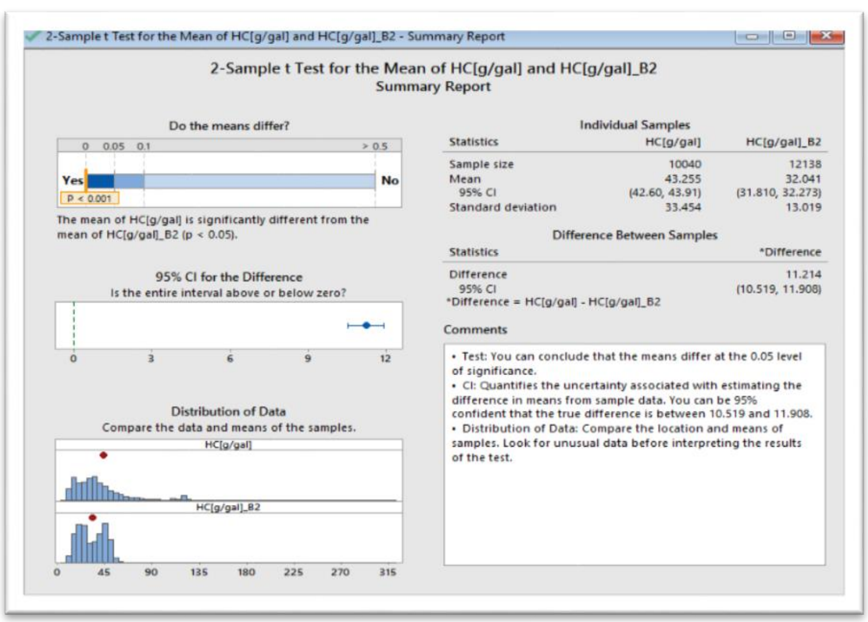


Fig D.17.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader3

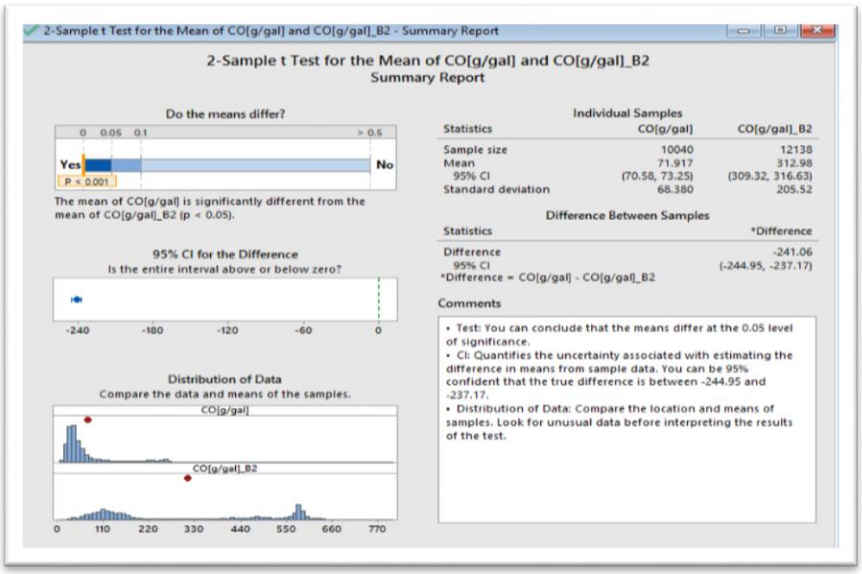


Fig D.18.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader3

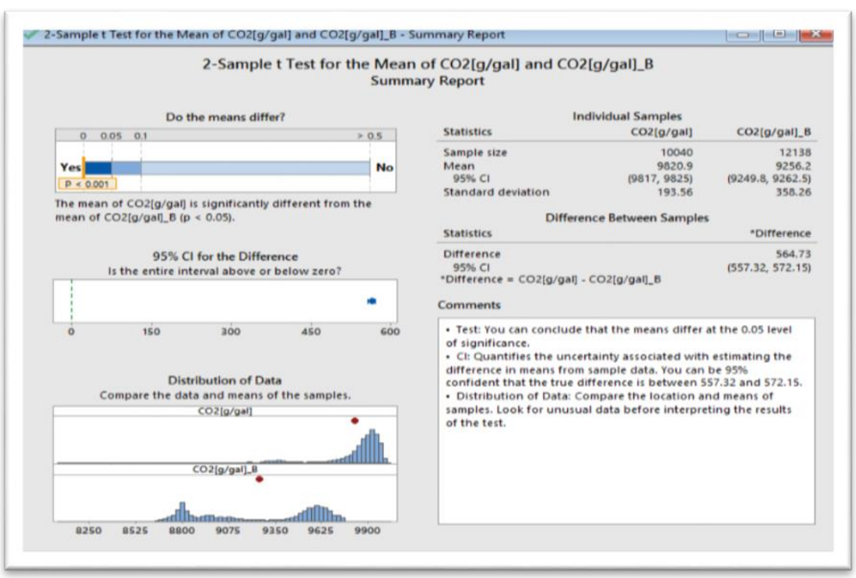


Fig D.19.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader3

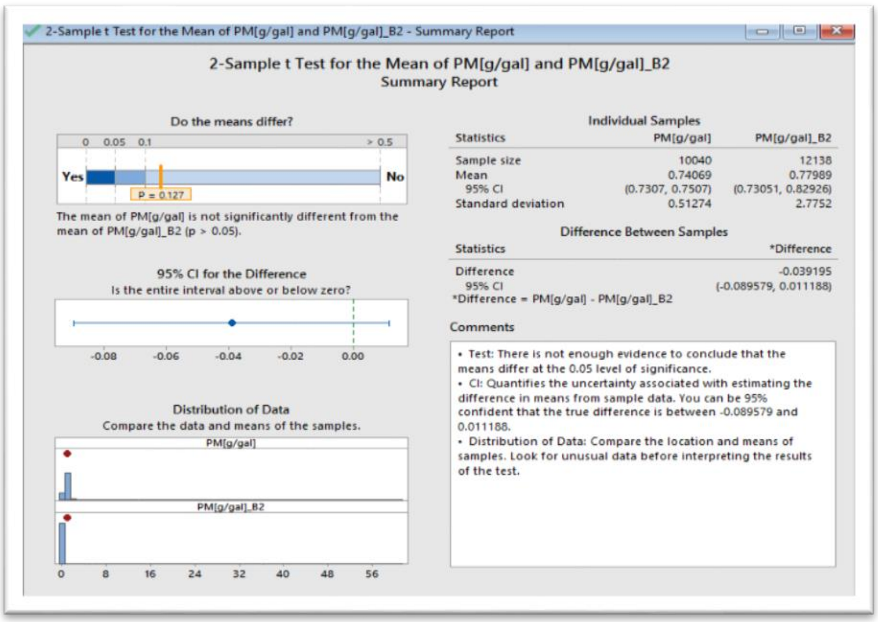


Fig D.20.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader3

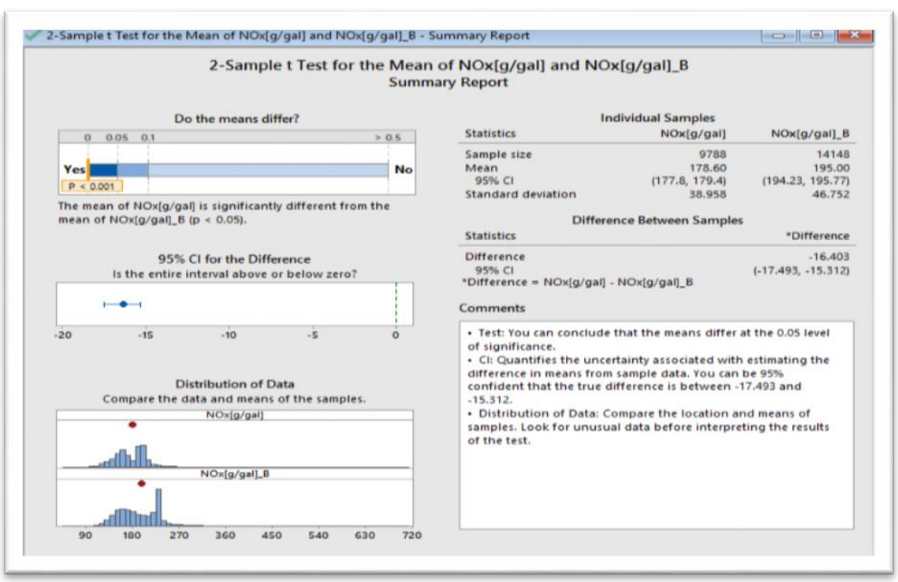


Fig D.21.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader4

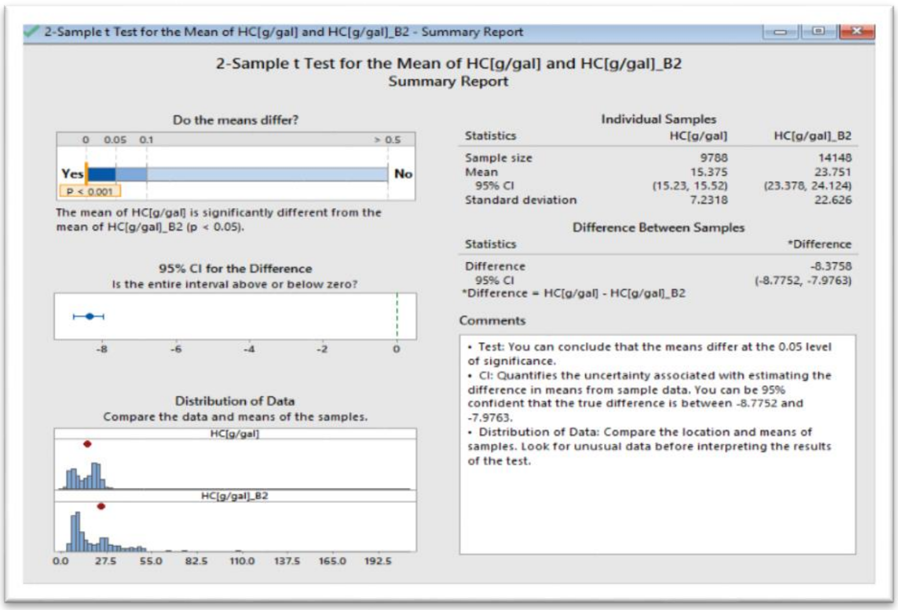


Fig D.22.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader4

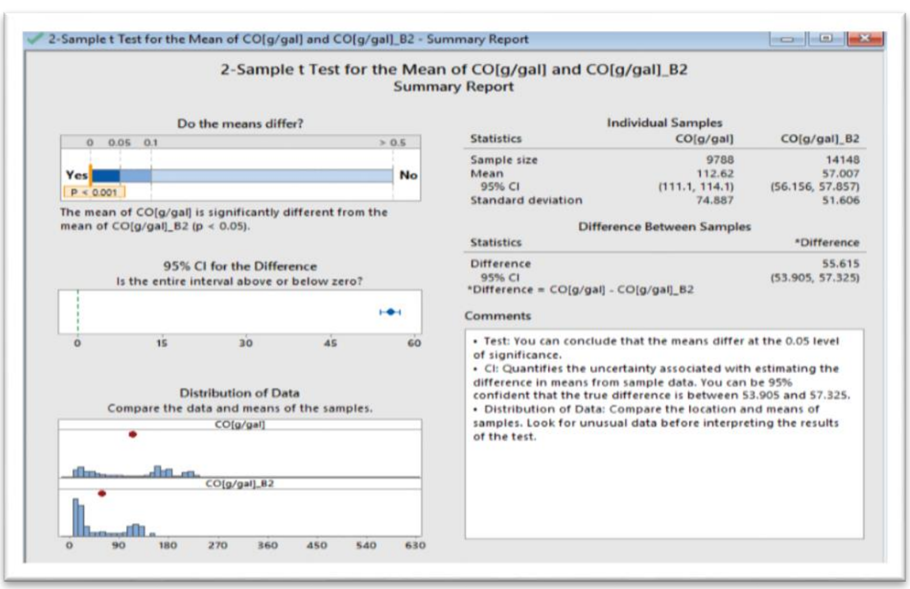


Fig D.23.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader4

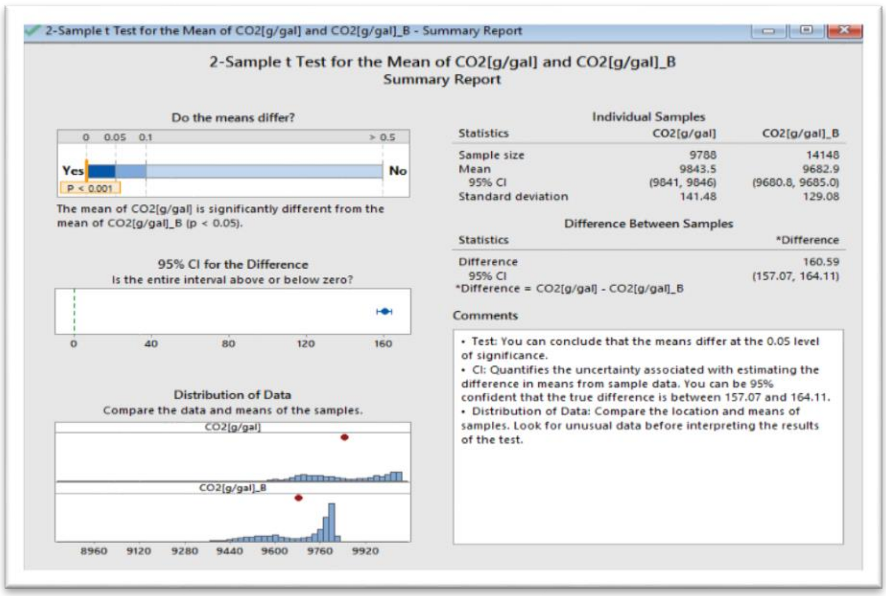


Fig D.24.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader4

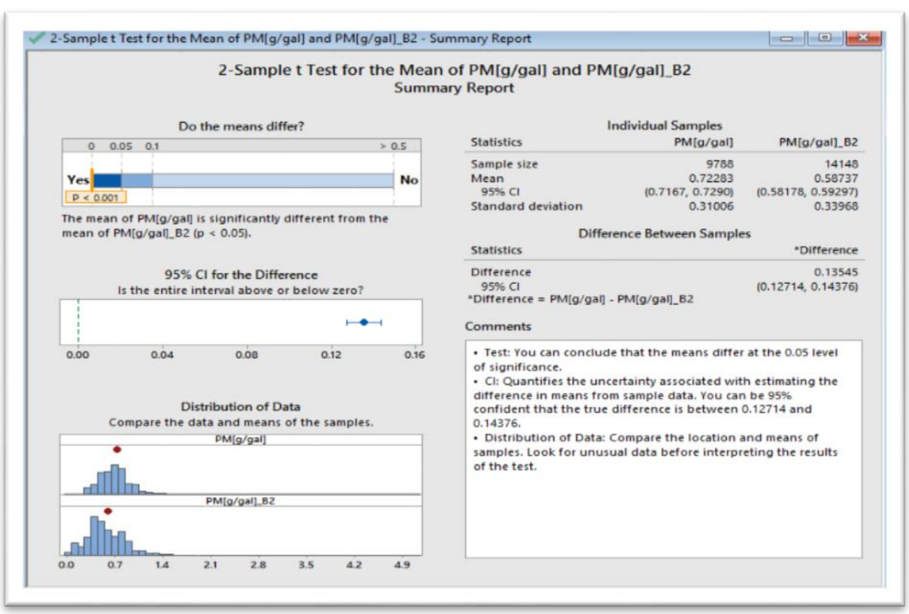


Fig D.25.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader4

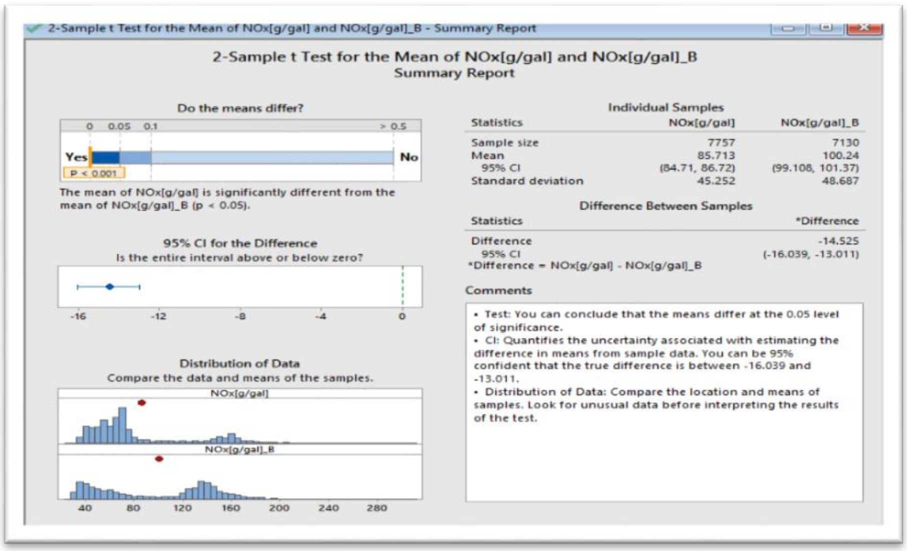


Fig D.26.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader5

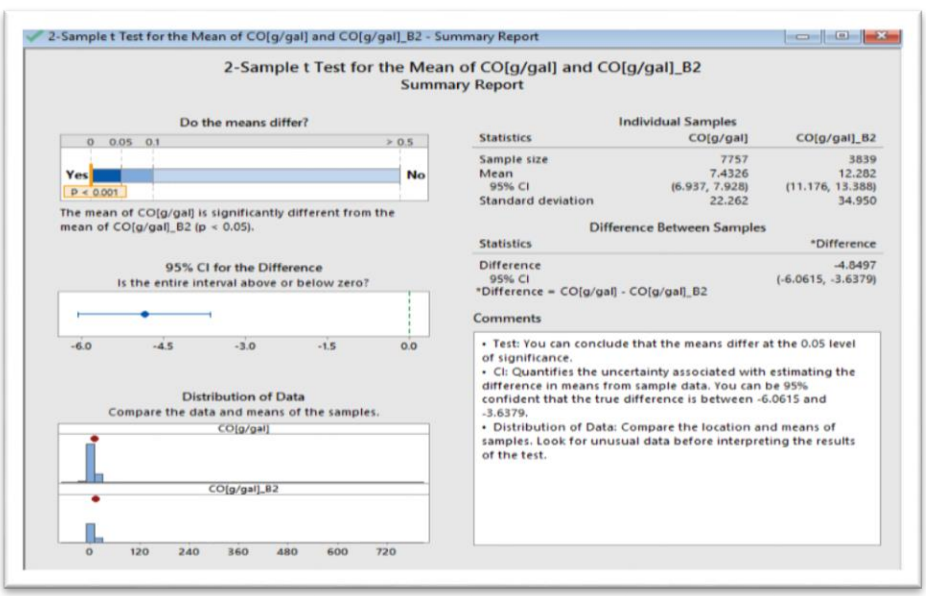


Fig D.27.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader5

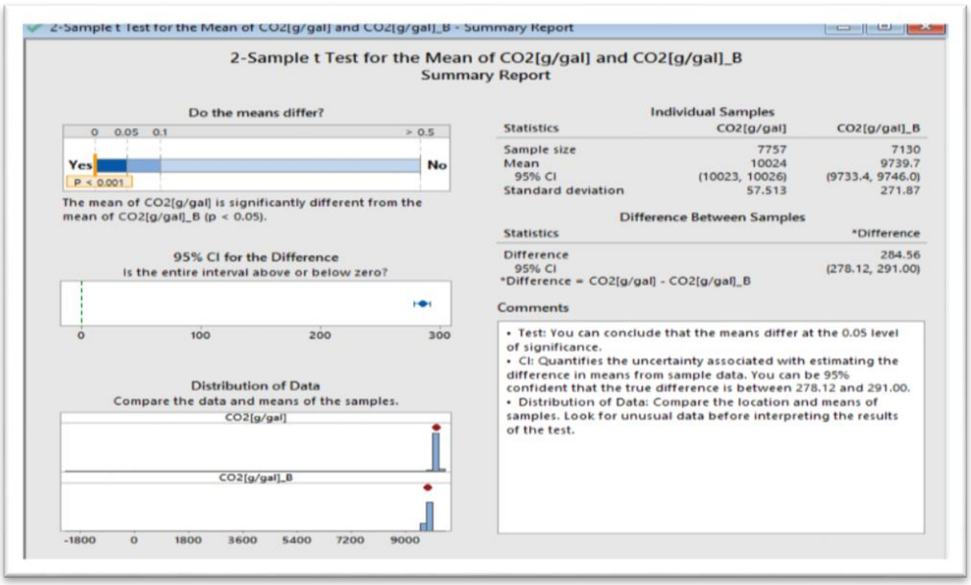


Fig D.28.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader5

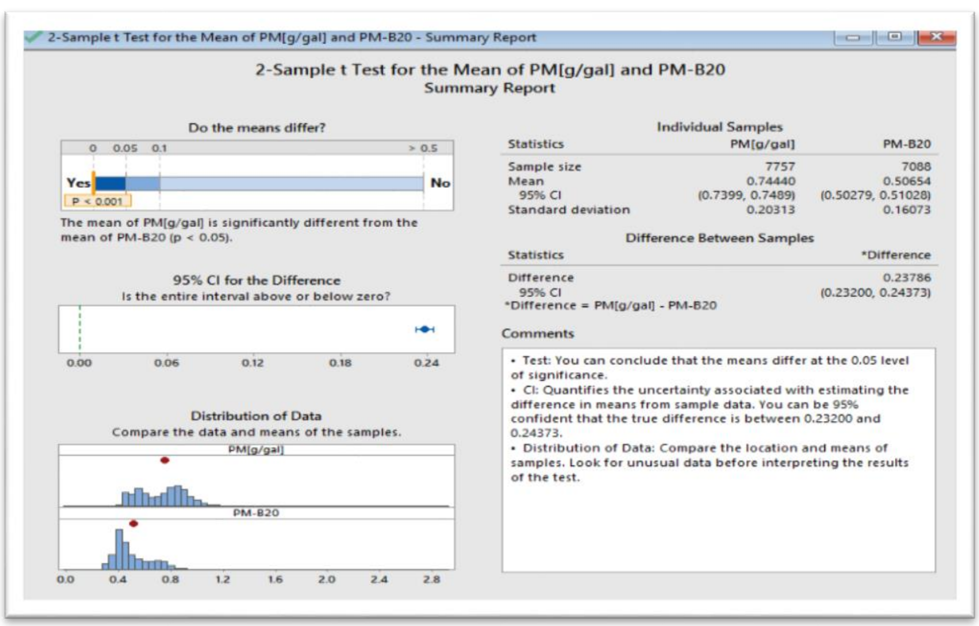


Fig D.29.2 Sample t-Test for the Mean of PM (g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader5

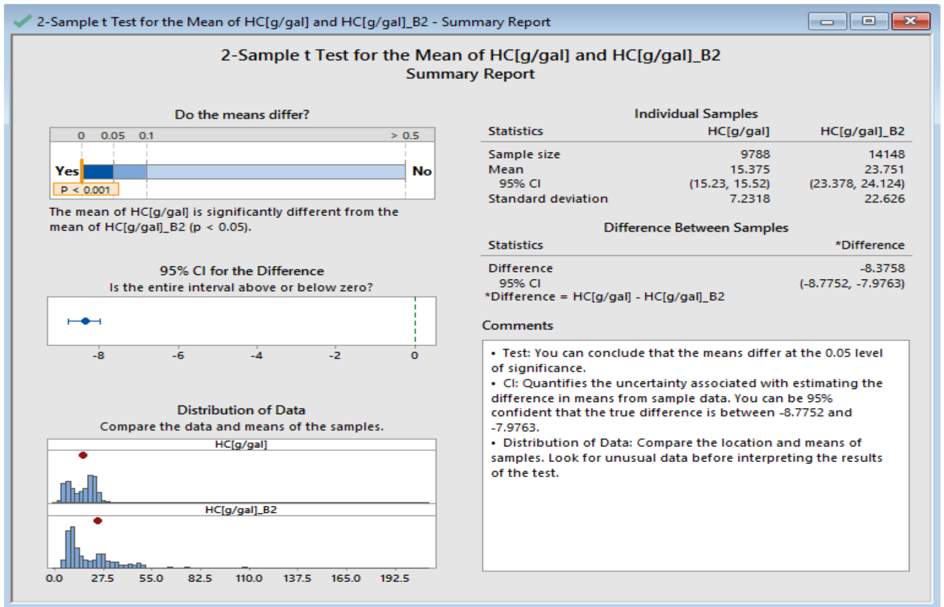


Fig D.30.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Motor Grader5

Appendix E

2 Sample t-Test for the Mean of B20 Biodiesel and Petroleum Diesel Wheel Loader's Pollutants

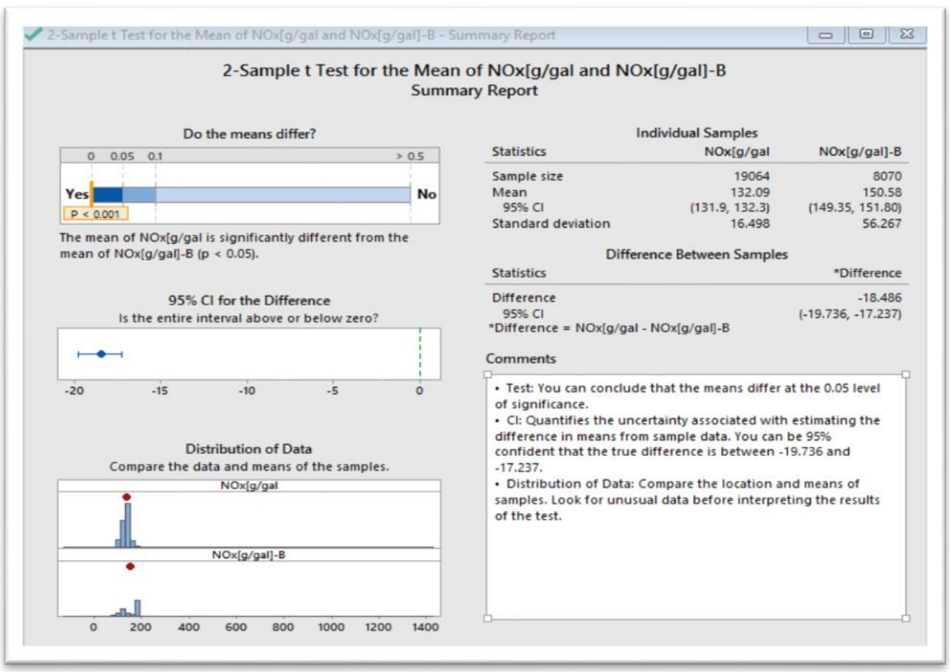


Fig E.1.2 Sample t-Test for the Mean of No_x(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader1

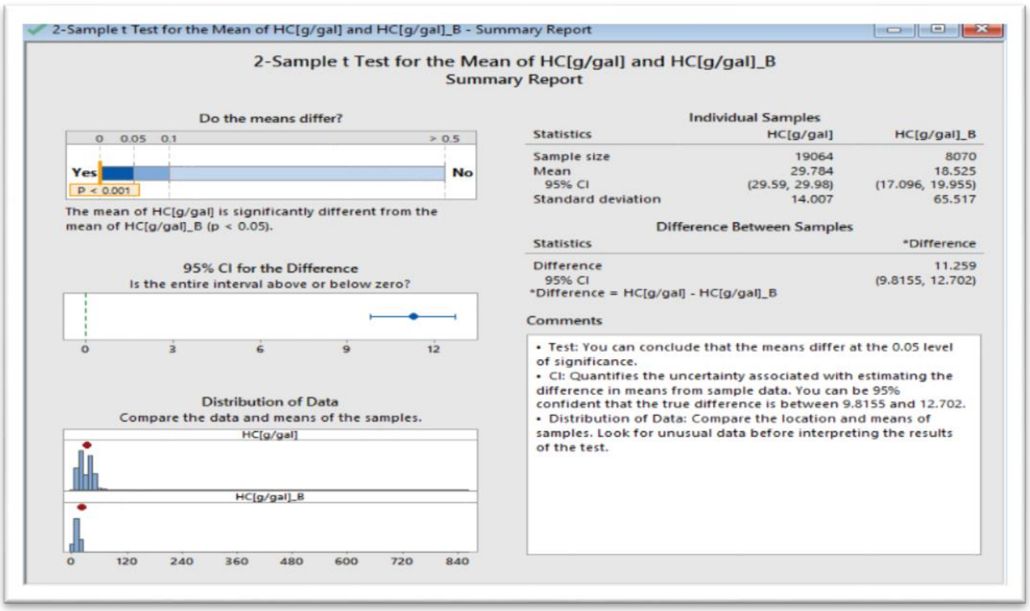


Fig E.2.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader1

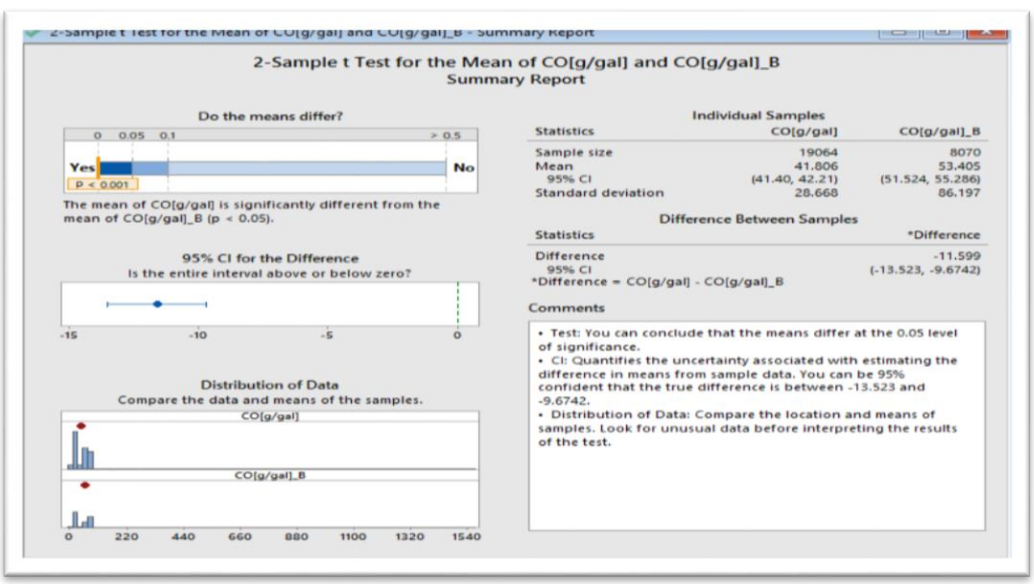


Fig E.3.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader1

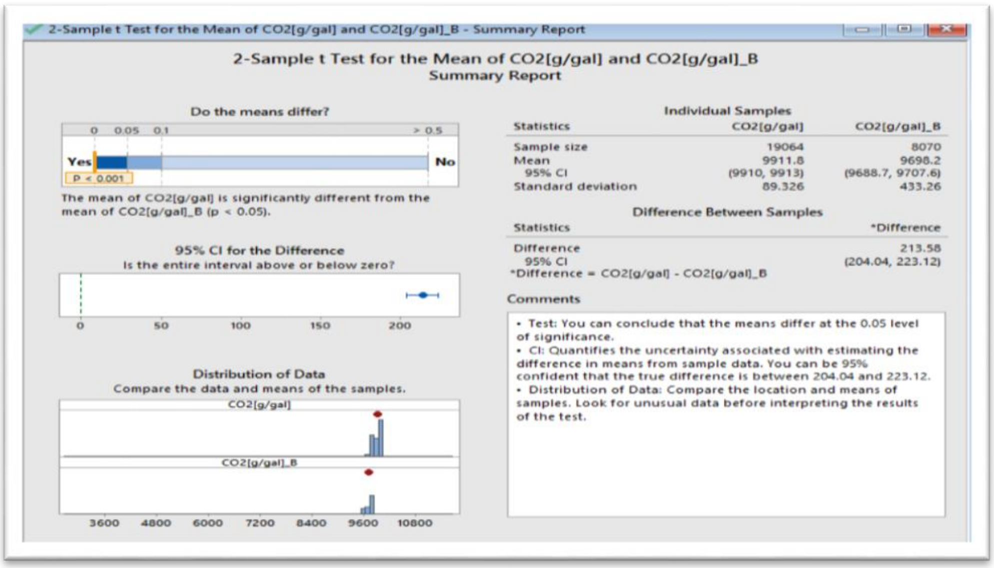


Fig E.4.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader1

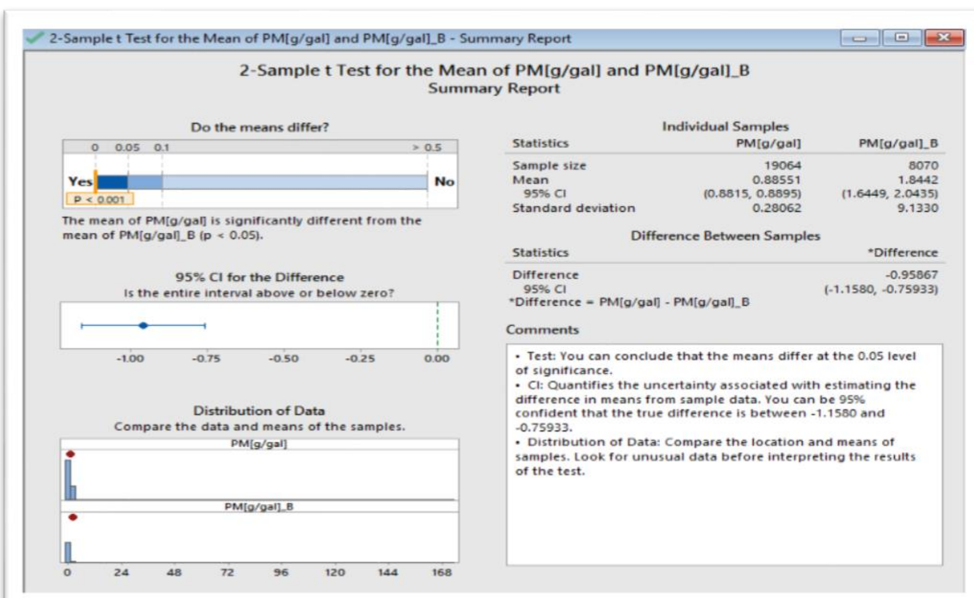


Fig E.5.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader1

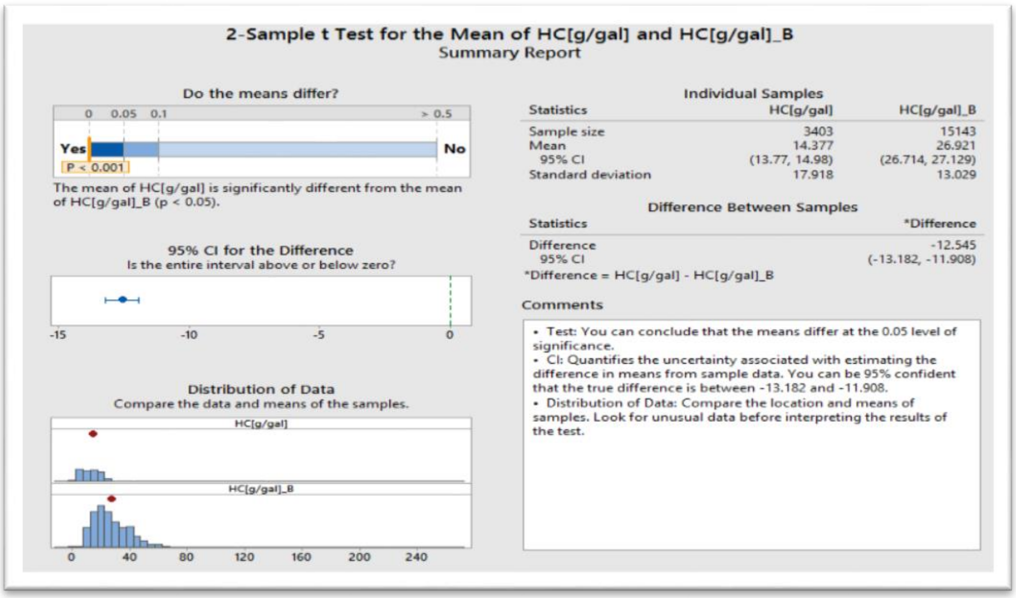


Fig E.6.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader2

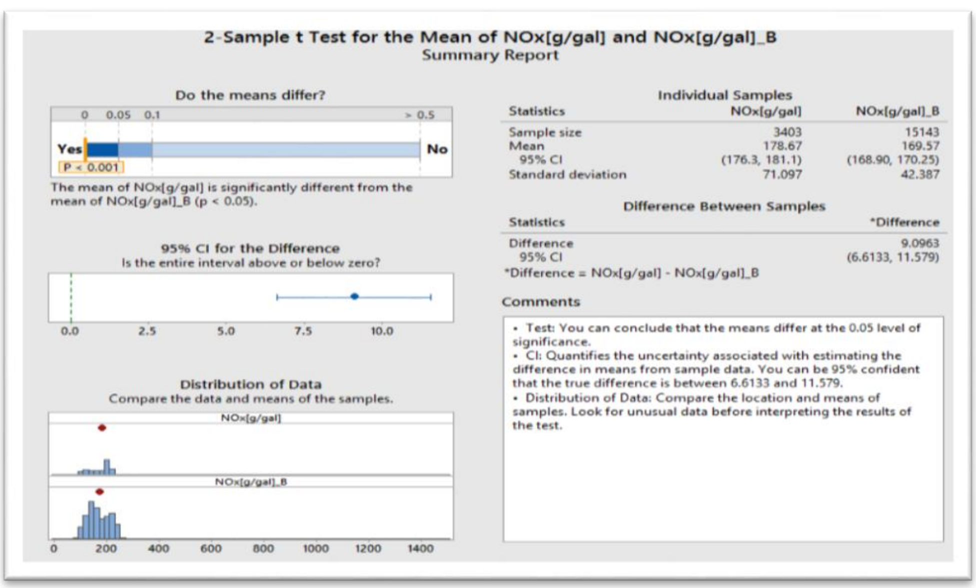


Fig E.7.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader2

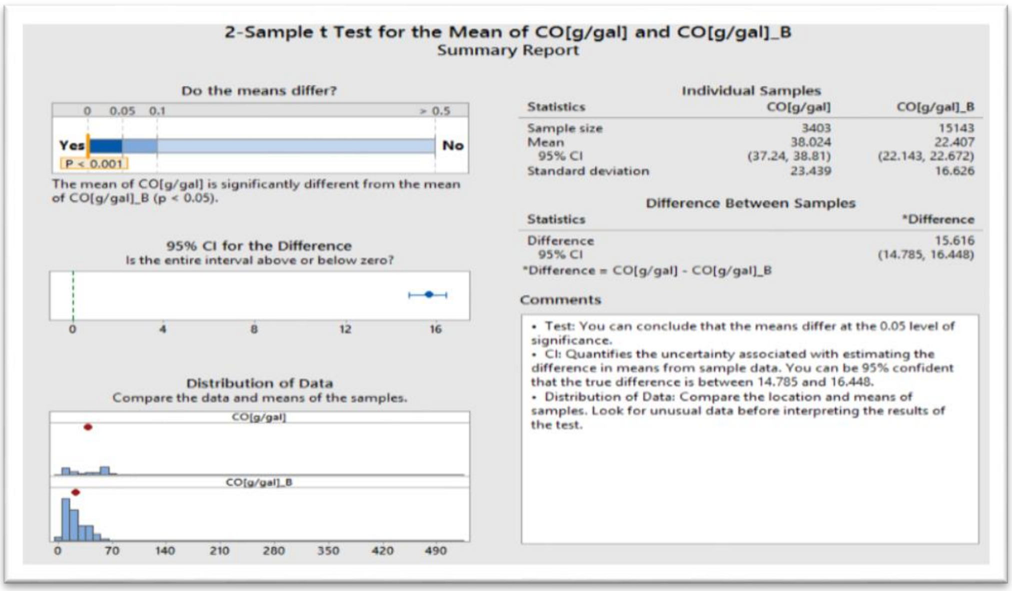


Fig E.8.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader2

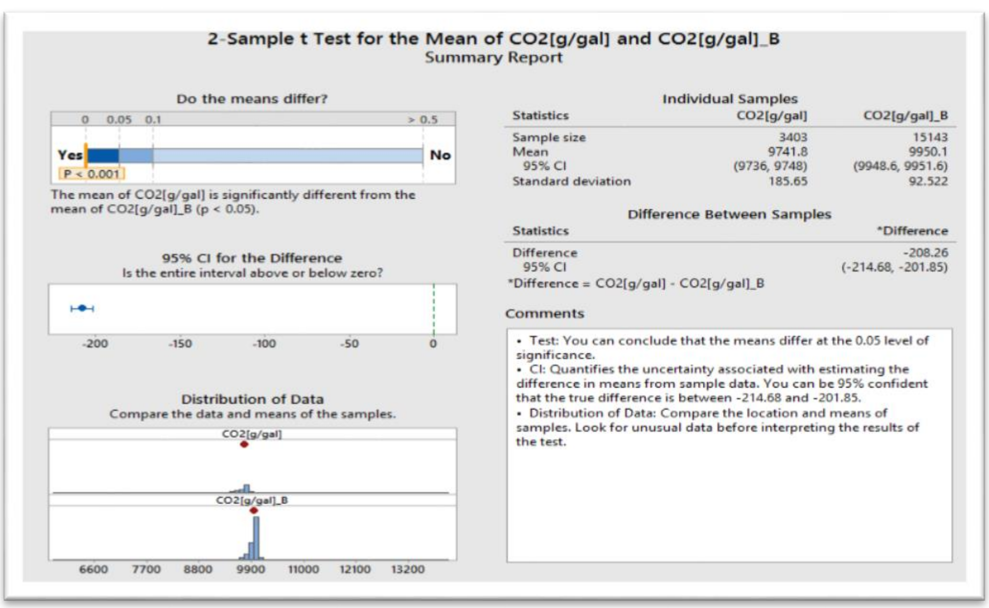


Fig E.9.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader2

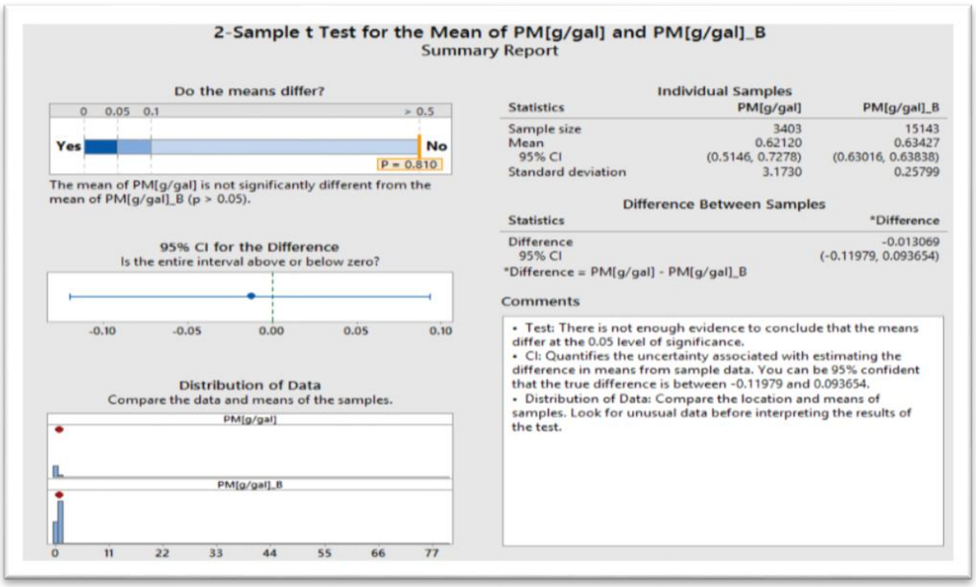


Fig E.10.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader2

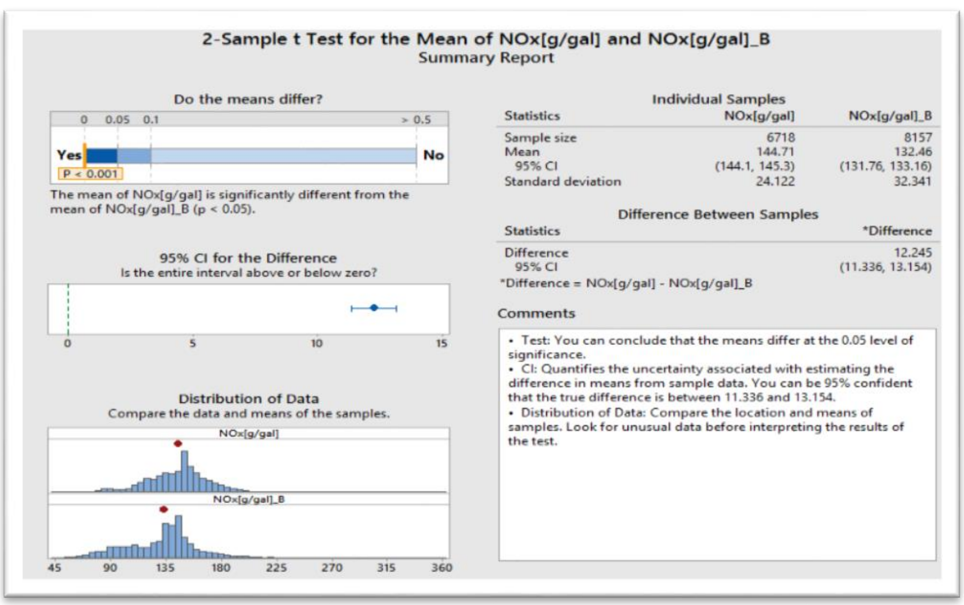


Fig E.11.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader3

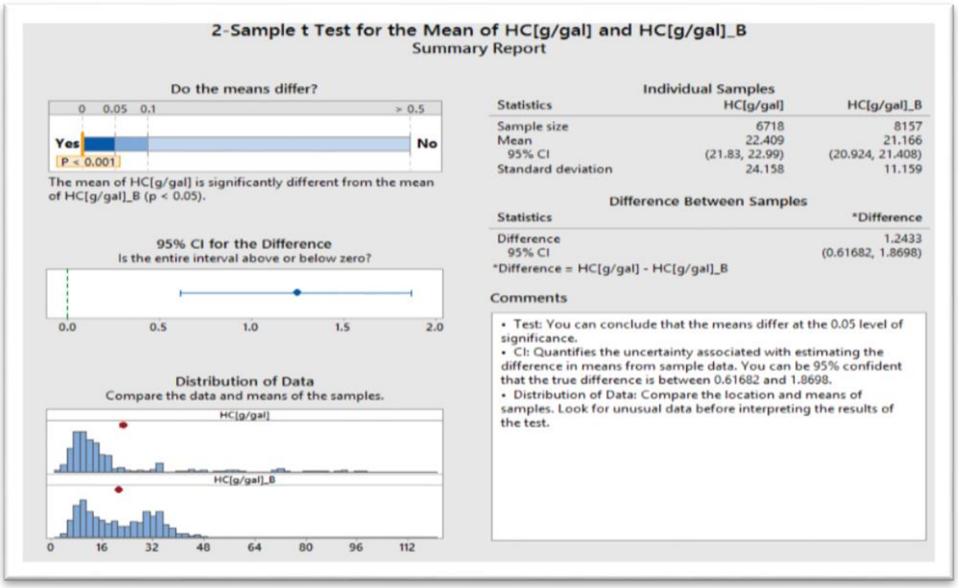


Fig E.12.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader3

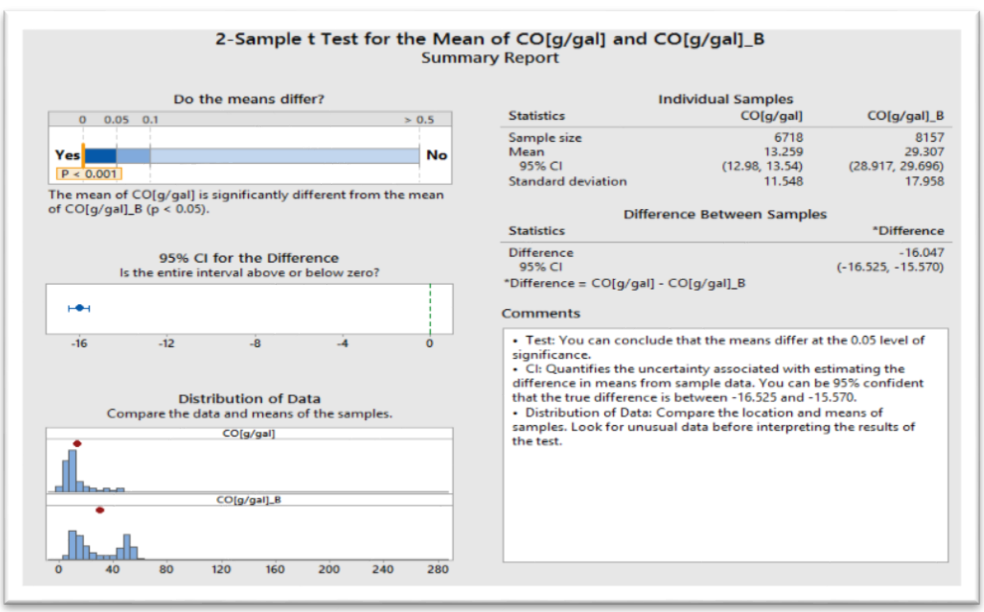


Fig E.13.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader3

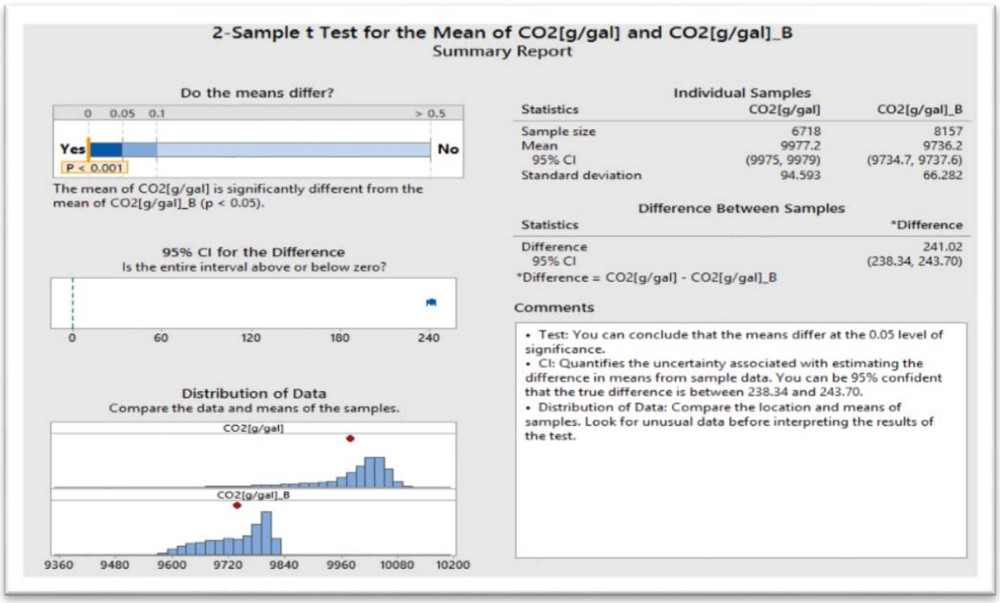


Fig E.14.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader3

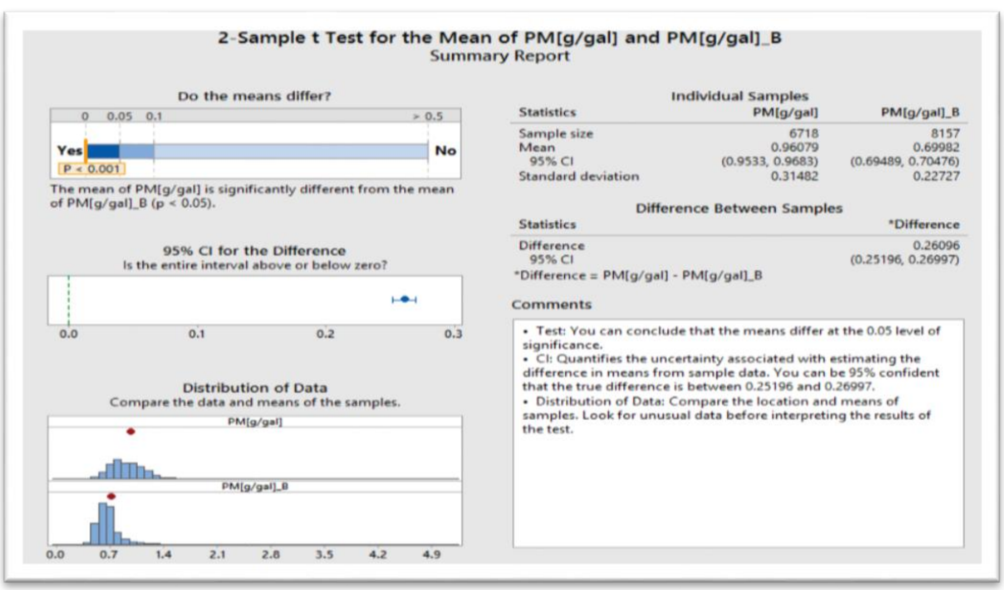


Fig E.15.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader3

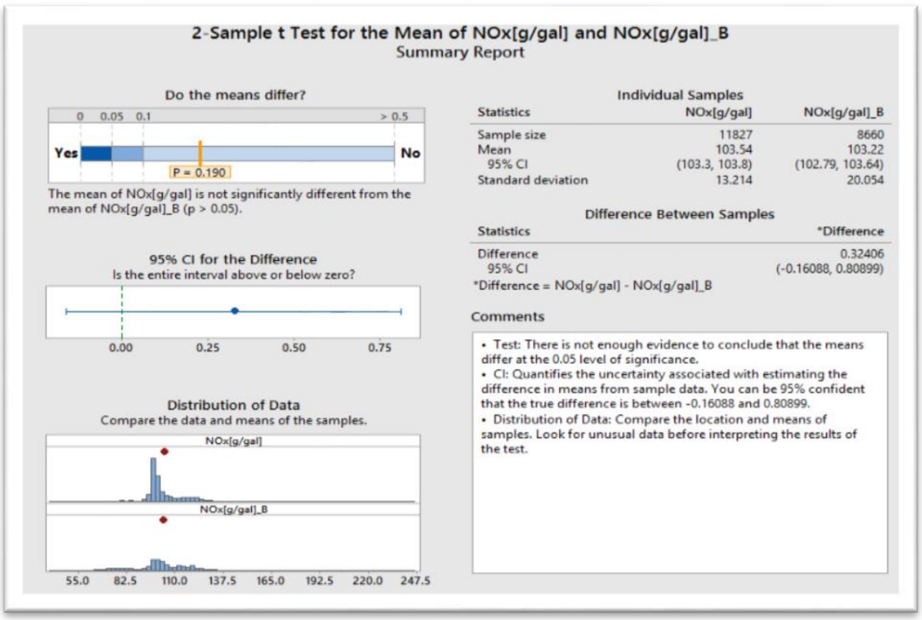


Fig E.16.2 Sample t-Test for the Mean of NO_x(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader4

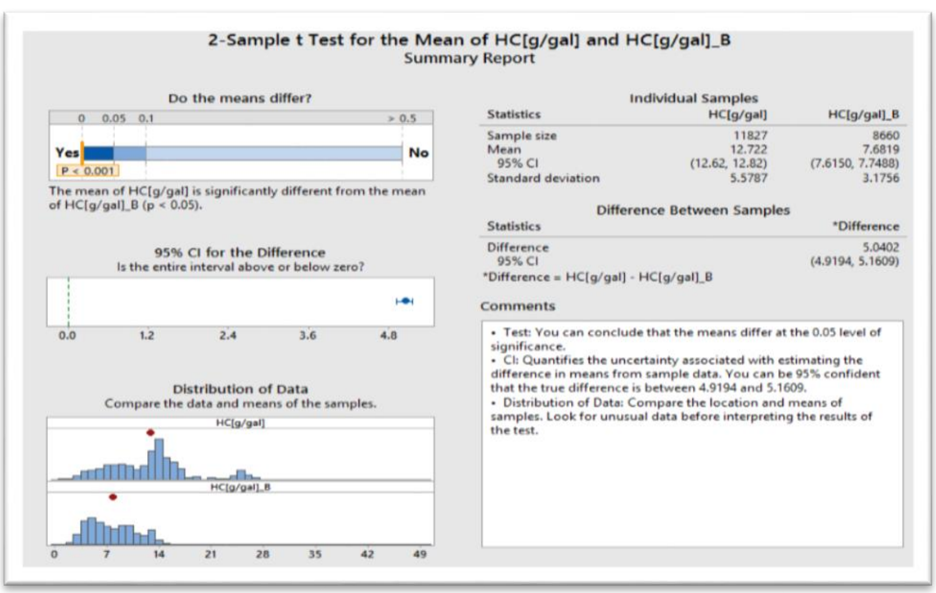


Fig E.17.2 Sample t-Test for the Mean of HC(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader4

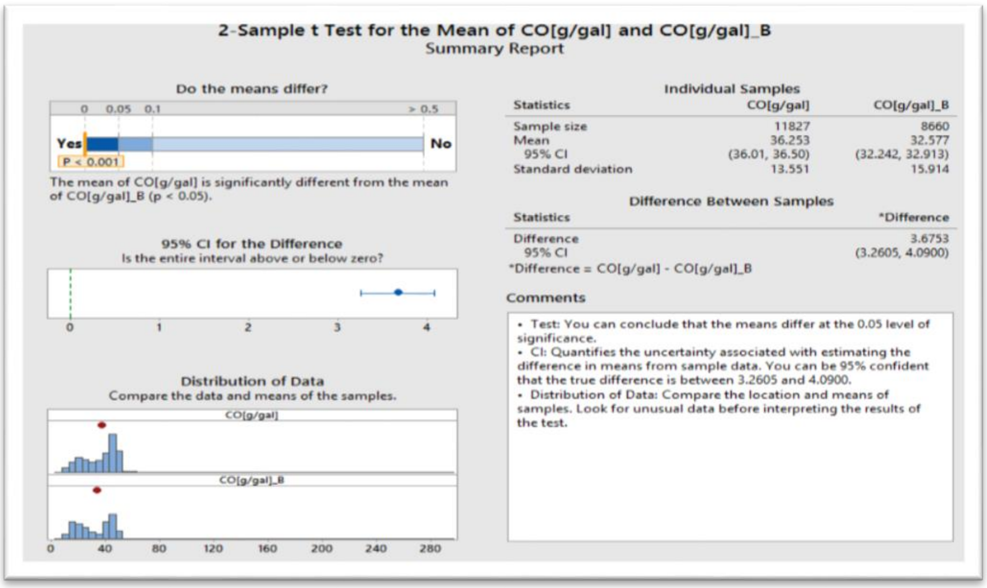


Fig E.18.2 Sample t-Test for the Mean of CO(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader4

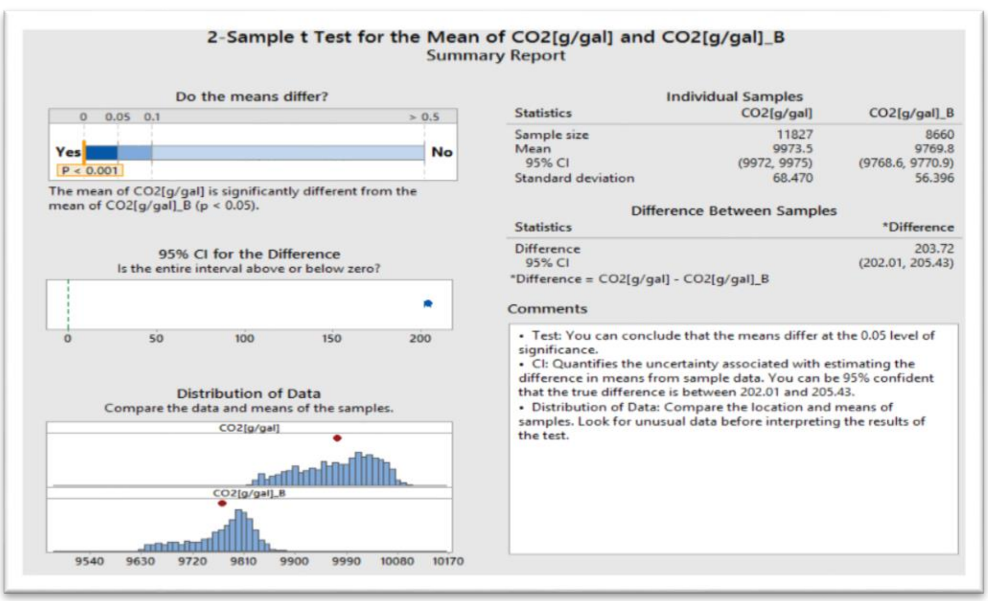


Fig E.19.2 Sample t-Test for the Mean of CO_2(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader4

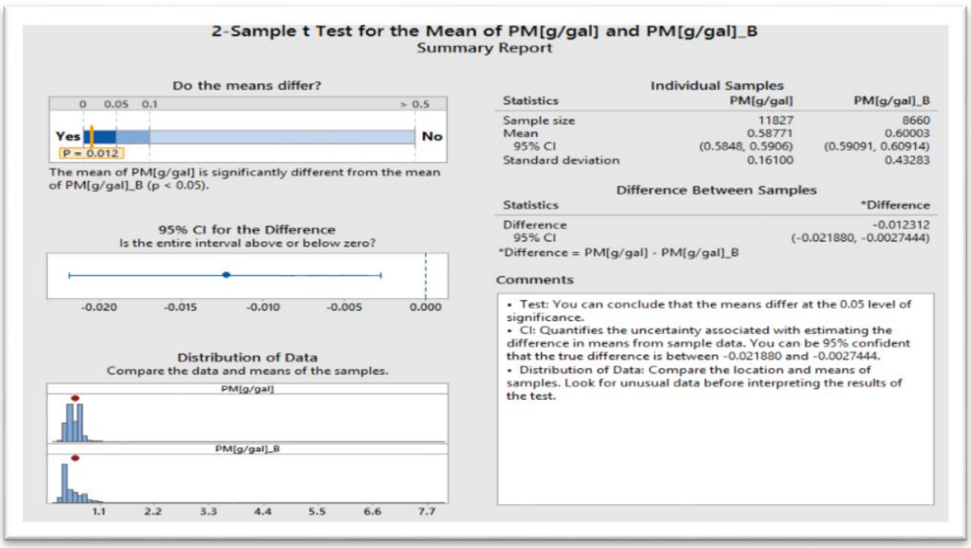


Fig E.20.2 Sample t-Test for the Mean of PM(g/gal) for B20 Biodiesel and Petroleum Diesel Wheel Loader4

Appendix F

Cumulative Frequency Diagram (CFD) of Each Pollutant on a Gram per Hour Basis

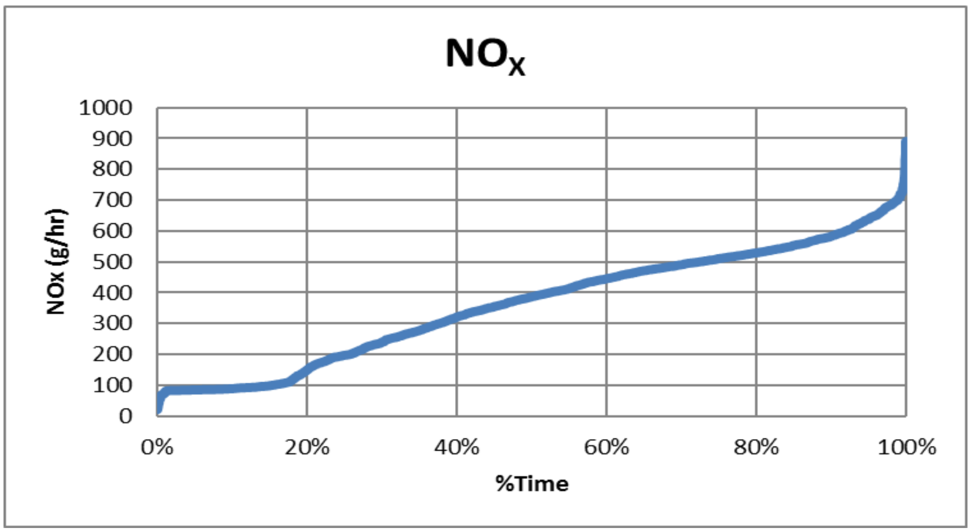


Fig F.1. Cumulative Frequency Diagram (CFD) of No_x(g/hr) for Dozer 1(Tier0)

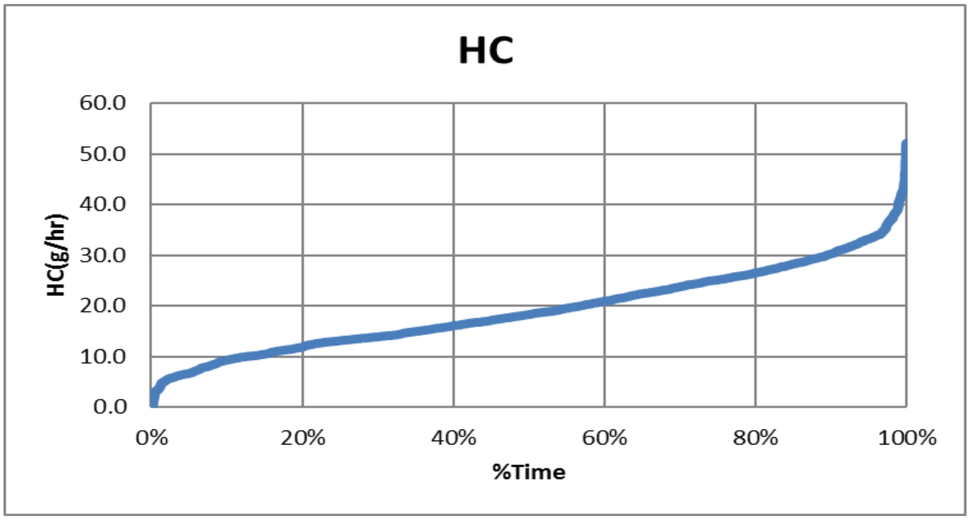


Fig F.2. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Dozer 1(Tier0)

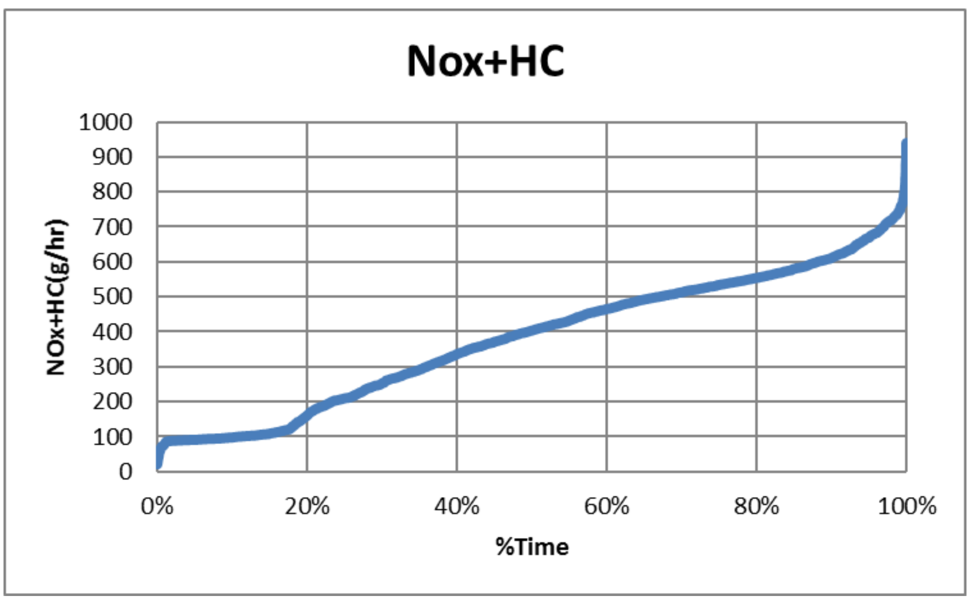


Fig F.3. Cumulative Frequency Diagram (CFD) of No_x +HC(g/hr) for Dozer 1(Tier0)

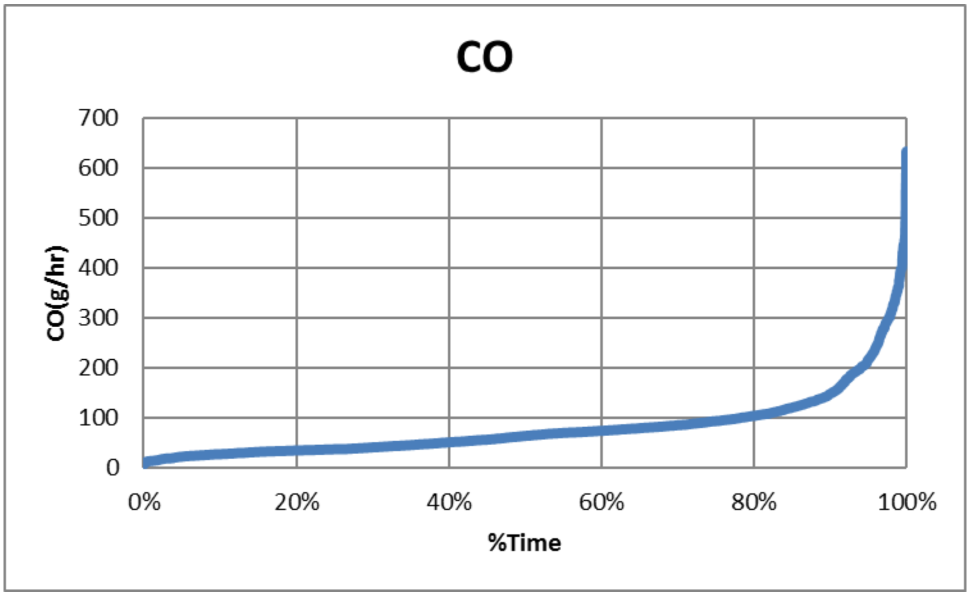


Fig F.4. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Dozer 1(Tier0)

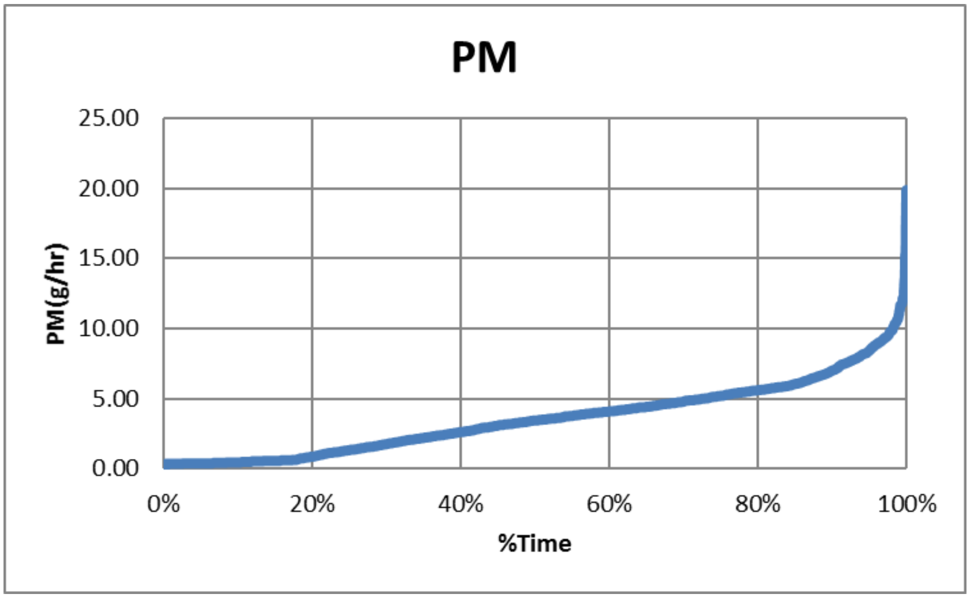


Fig F.5. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Dozer 1(Tier0)

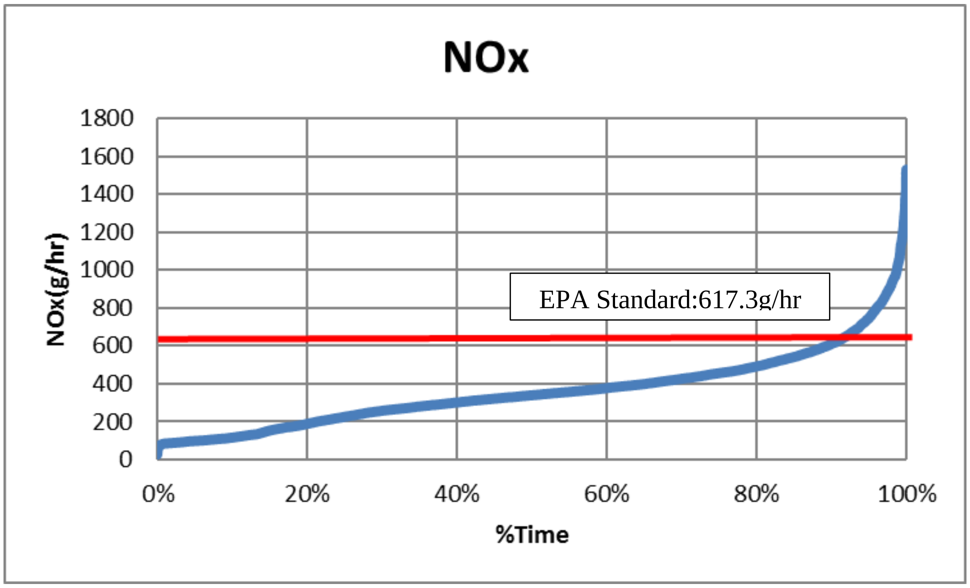


Fig F.6. Cumulative Frequency Diagram (CFD) of No_x(g/hr) for Dozer 3(Tier1)

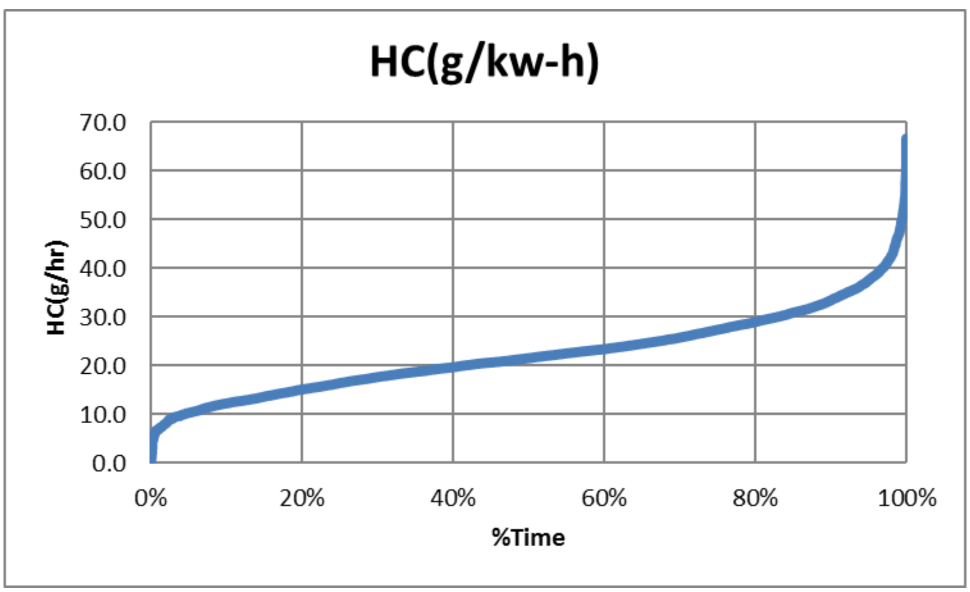


Fig F.7. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Dozer 3(Tier1)

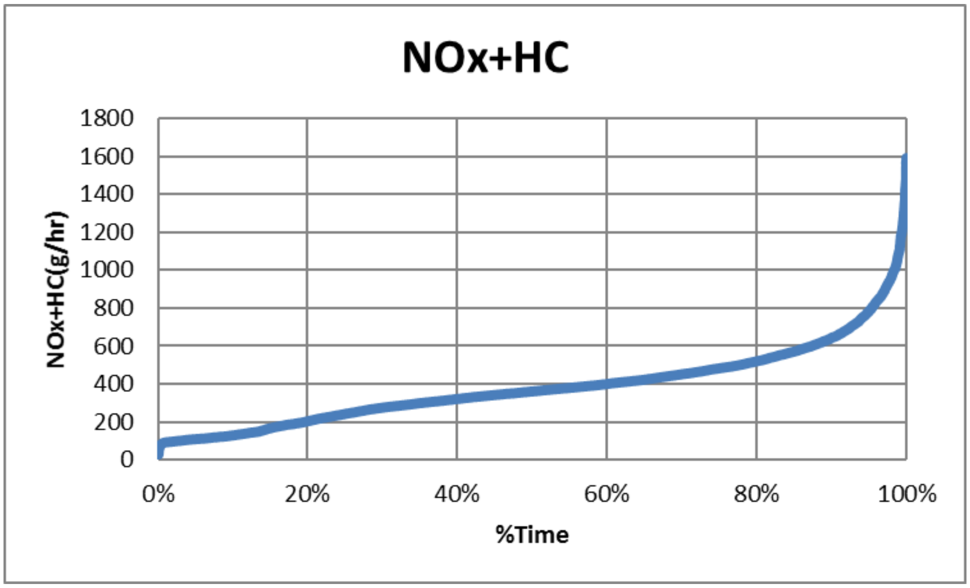


Fig F.8. Cumulative Frequency Diagram (CFD) of No_x+HC(g/hr) for Dozer 3(Tier1)

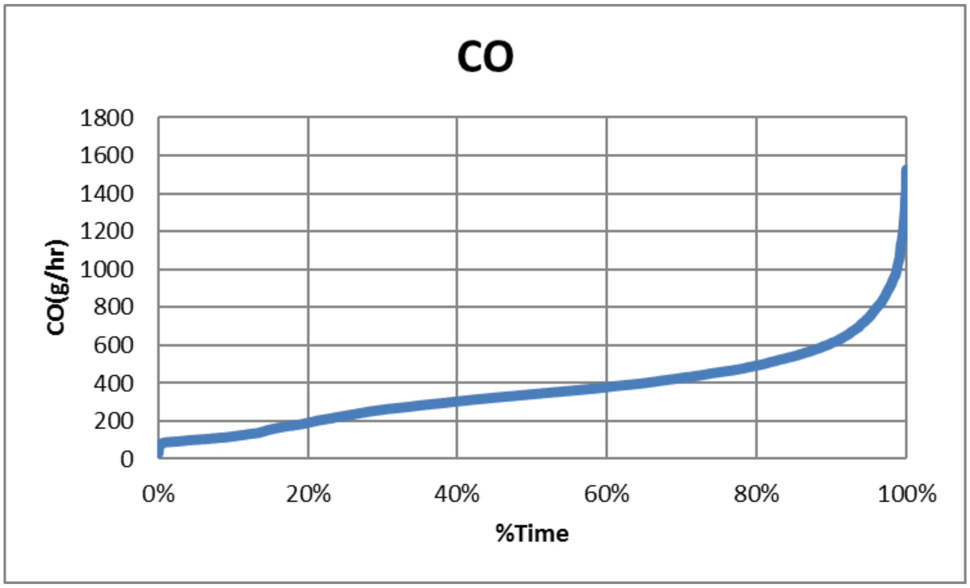


Fig F.9. Cumulative Frequency Diagram (CFD) of CO (g/hr) for Dozer 3(Tier1)

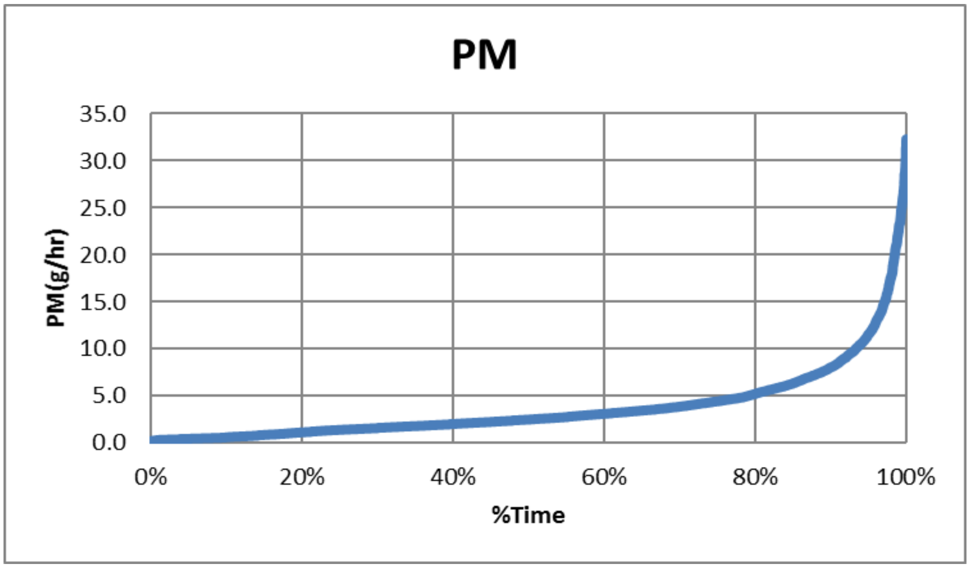


Fig F.10. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Dozer 3(Tier1)

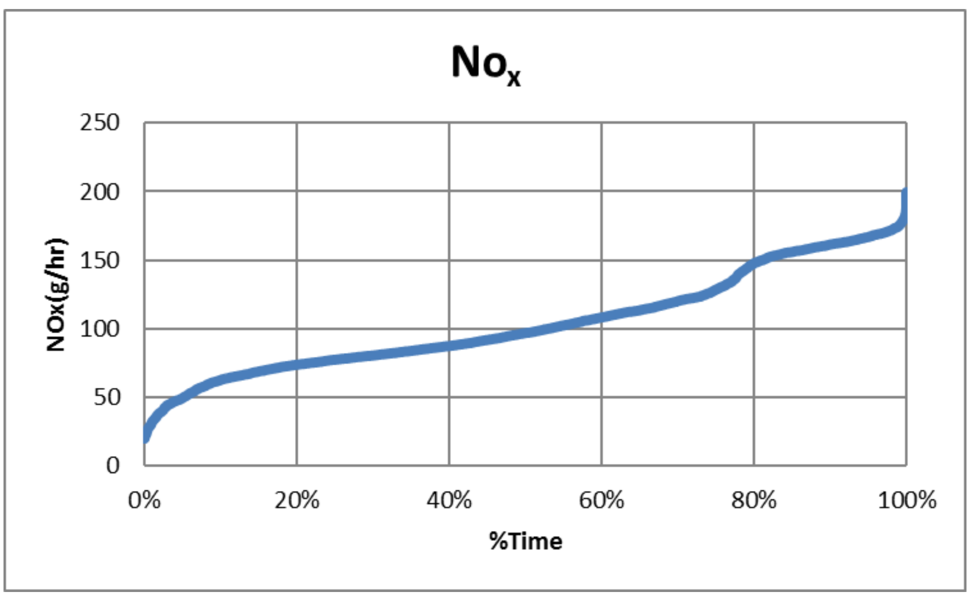


Fig F.11. Cumulative Frequency Diagram (CFD) of No$_x$(g/hr) for Dozer 6(Tier2)

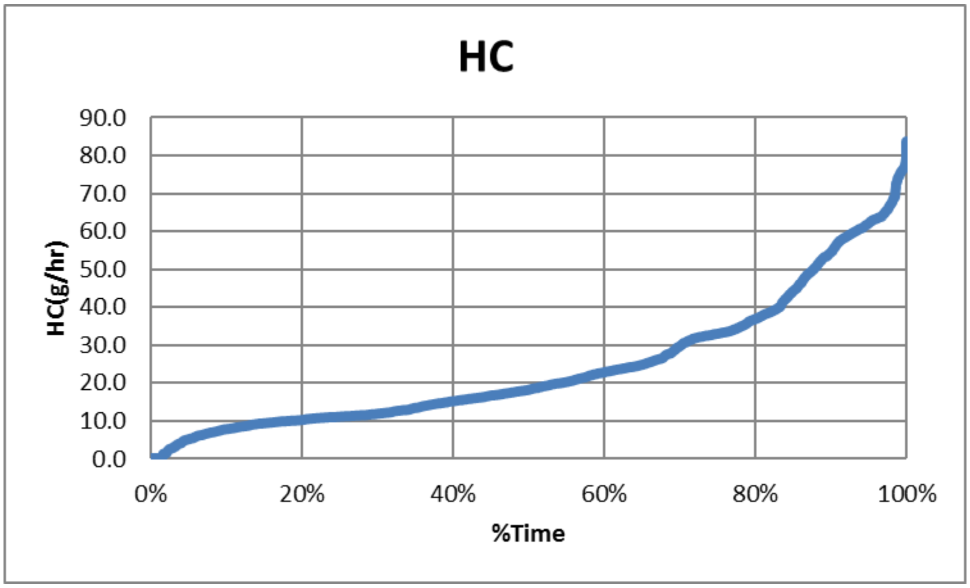


Fig F.12. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Dozer 6(Tier2)

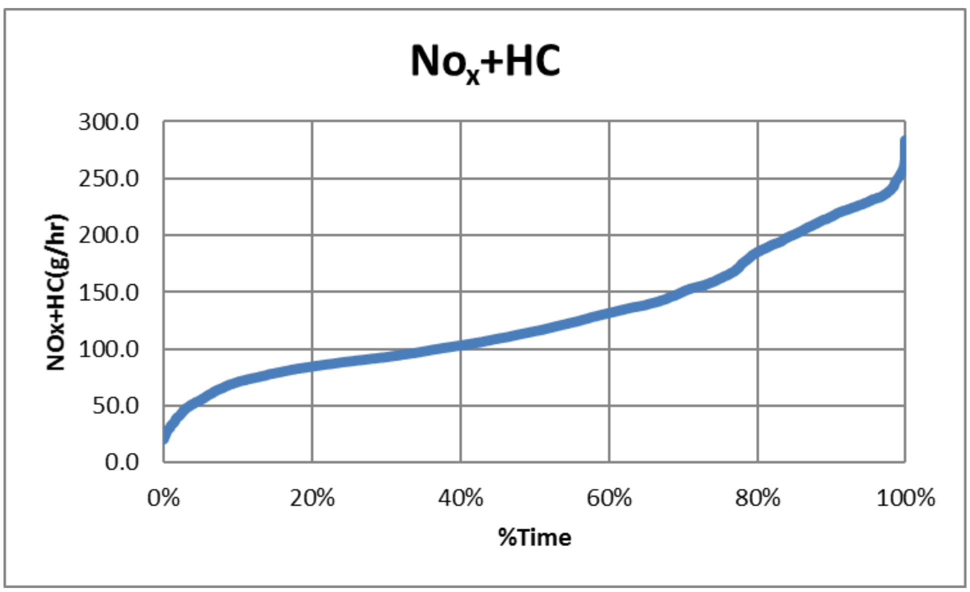


Fig F.13. Cumulative Frequency Diagram (CFD) of No_x+HC(g/hr) for Dozer 6(Tier2)

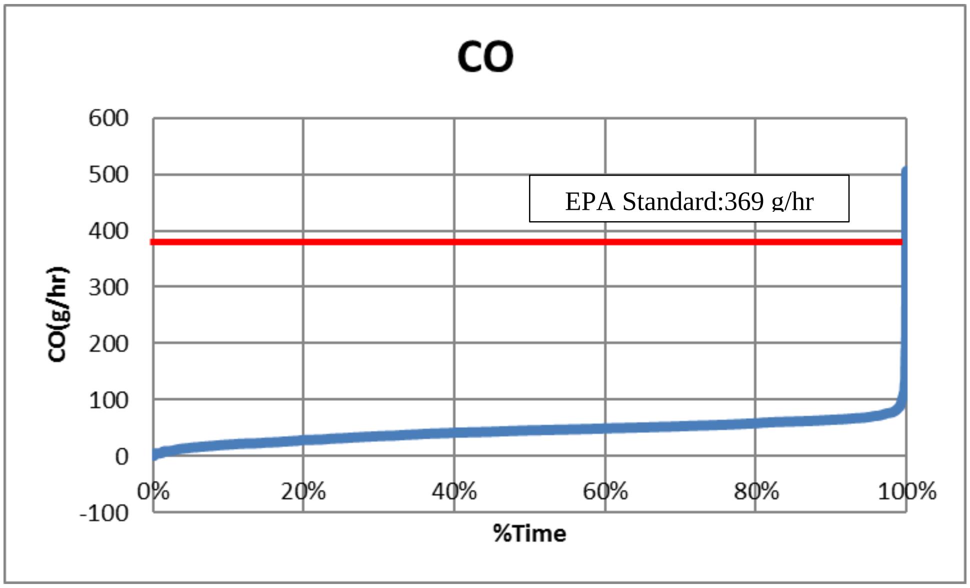


Fig F.14. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Dozer 6(Tier2)

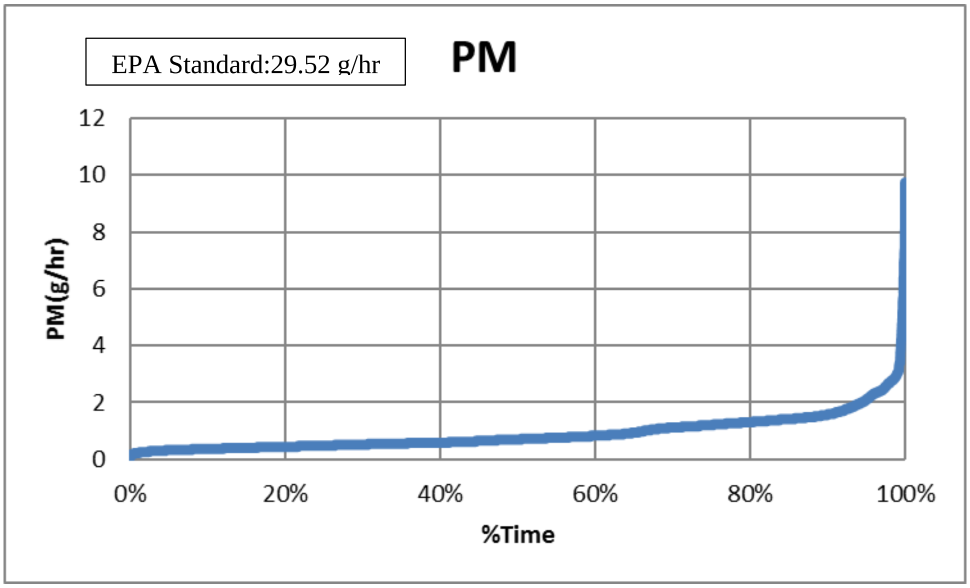


Fig F.15. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Dozer 6(Tier2)

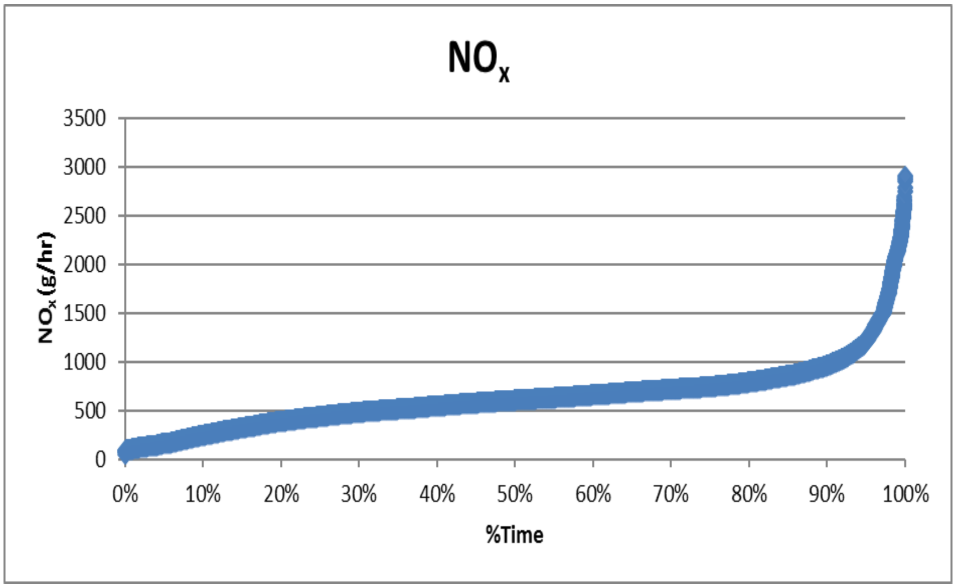


Fig F.16. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Motor Grader 4 (Tier0)

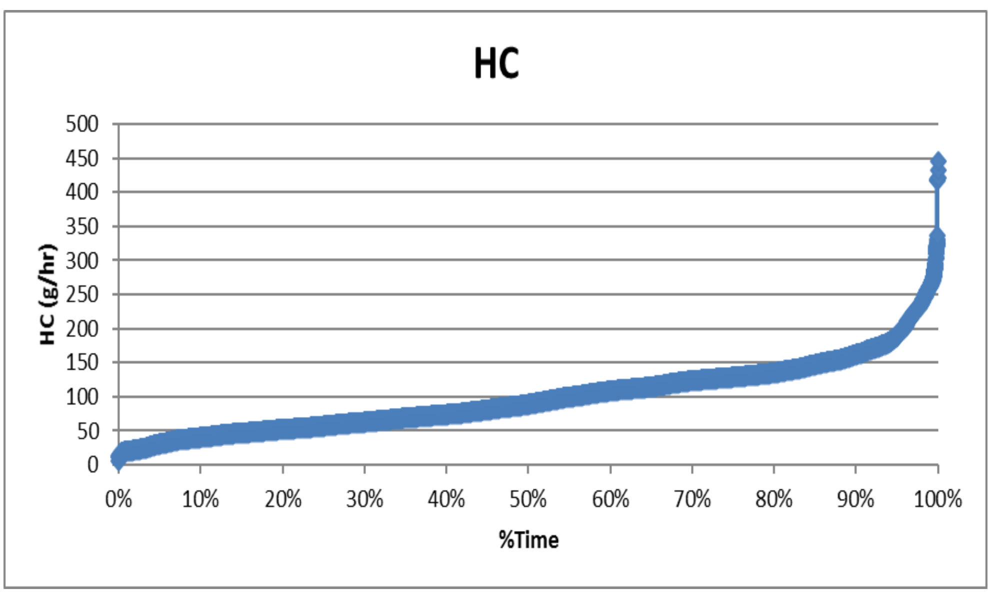


Fig F.17. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Motor Grader 4 (Tier0)

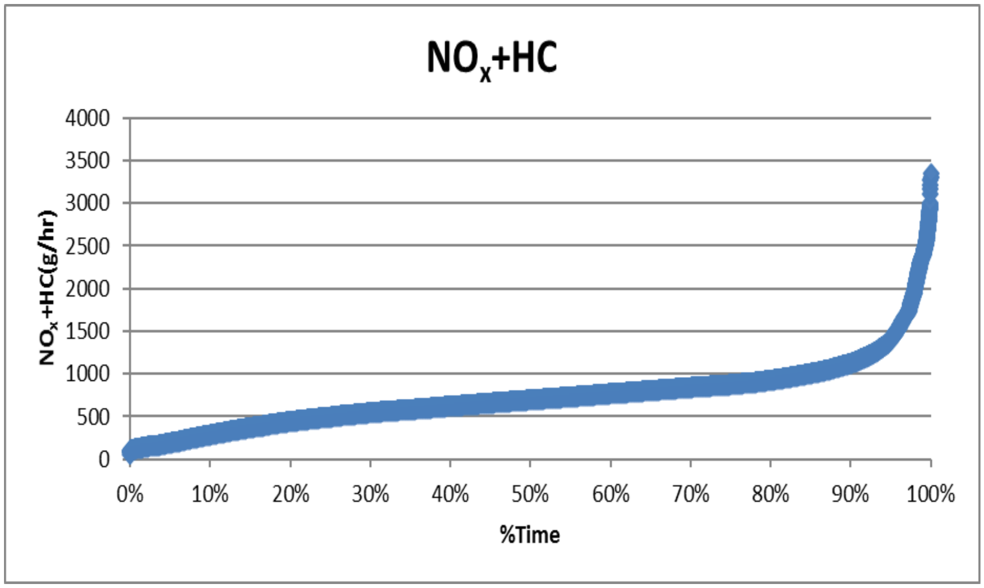


Fig F.18. Cumulative Frequency Diagram (CFD) of No_x+HC(g/hr) for Motor Grader 4 (Tier0)

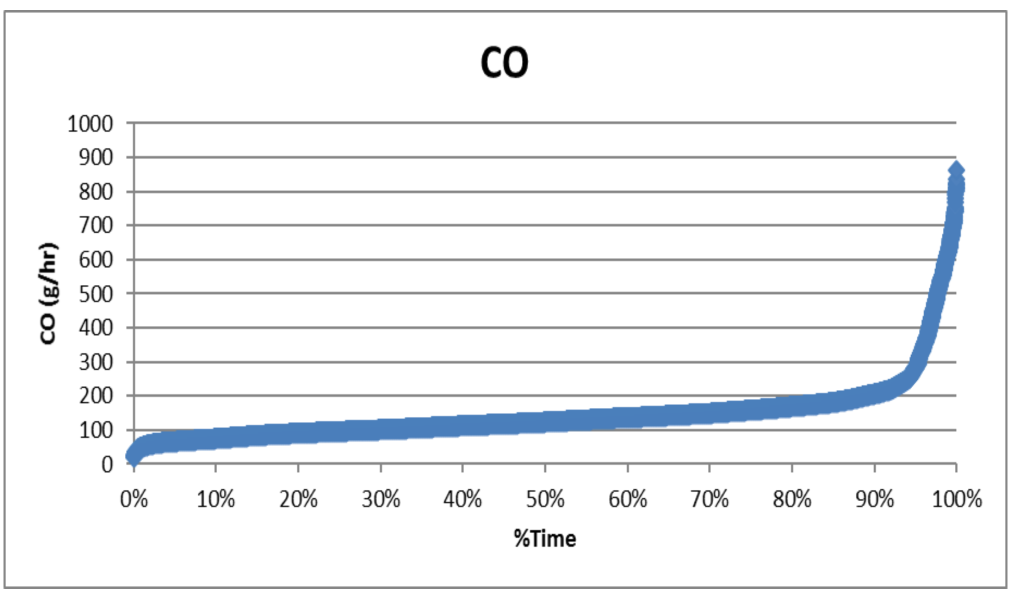


Fig F.19. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Motor Grader 4 (Tier0)

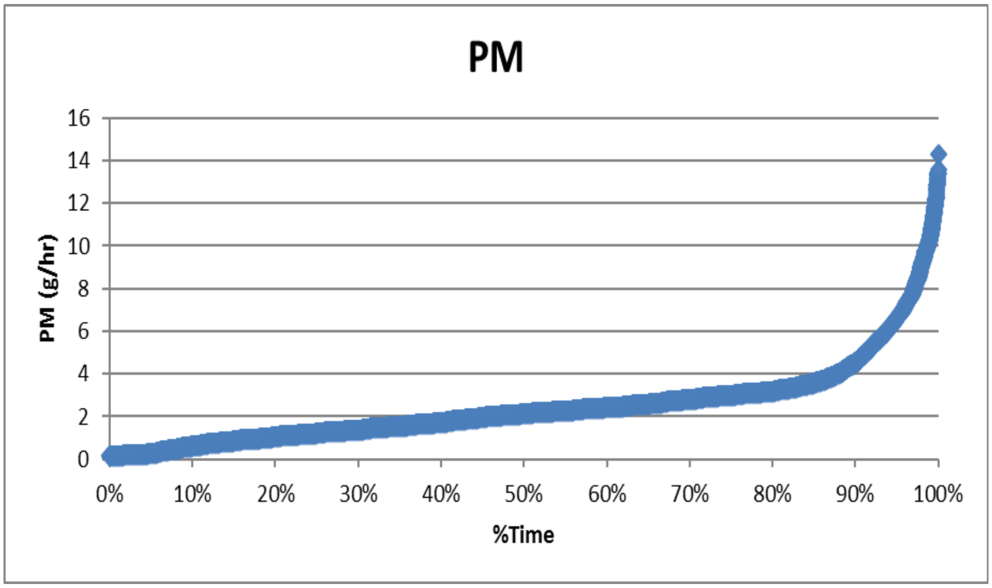


Fig F.20. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Motor Grader 4 (Tier0)

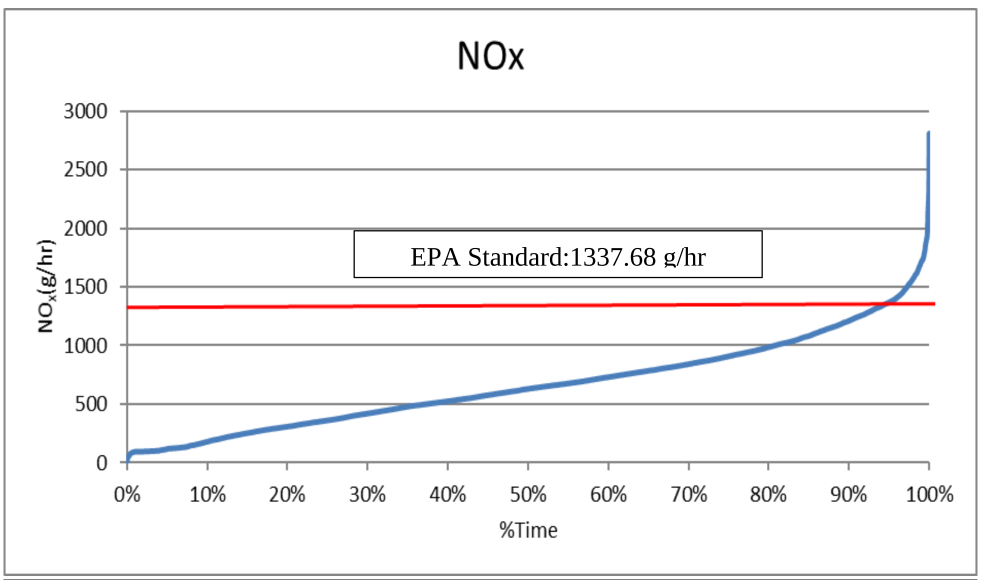


Fig F.21. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Motor Grader 1 (Tier1)

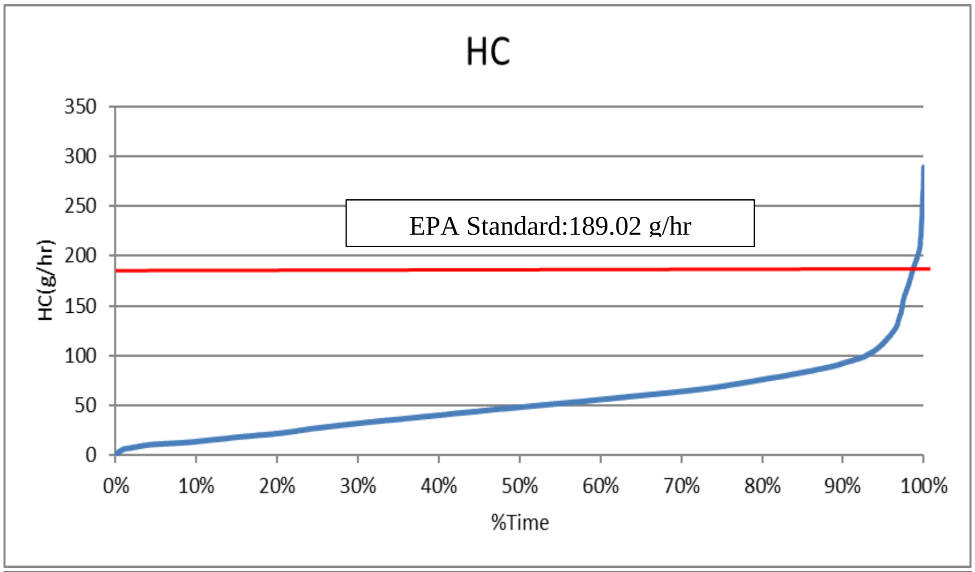


Fig F.22. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Motor Grader 1 (Tier1)

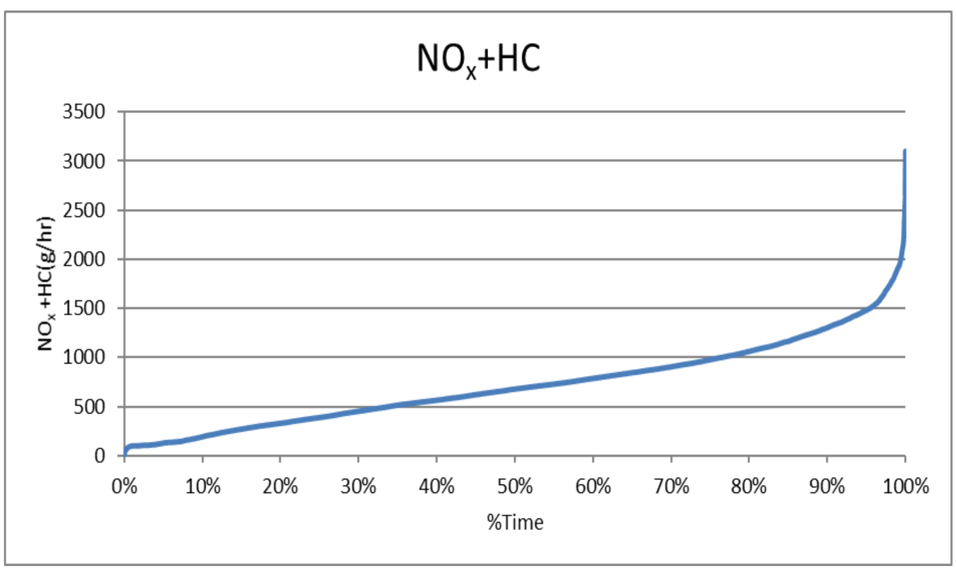


Fig F.23. Cumulative Frequency Diagram (CFD) of NO_x+HC(g/hr) for Motor Grader 1 (Tier1)

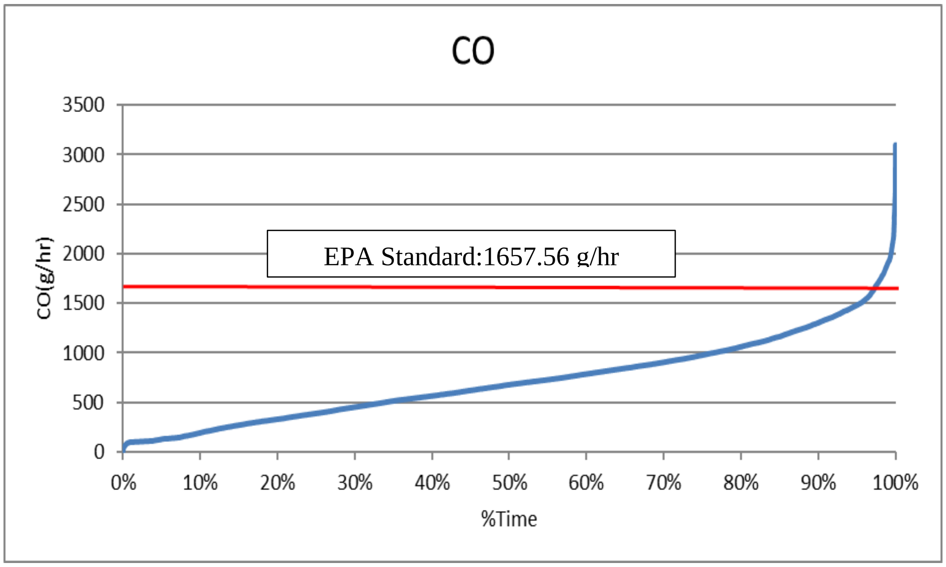


Fig F.24. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Motor Grader 1 (Tier1)

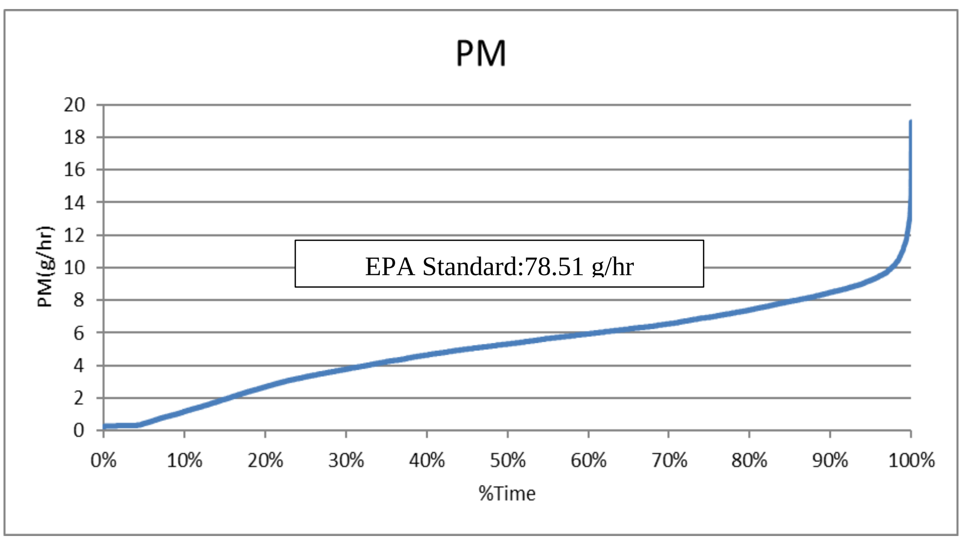


Fig F.25. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Motor Grader 1 (Tier1)

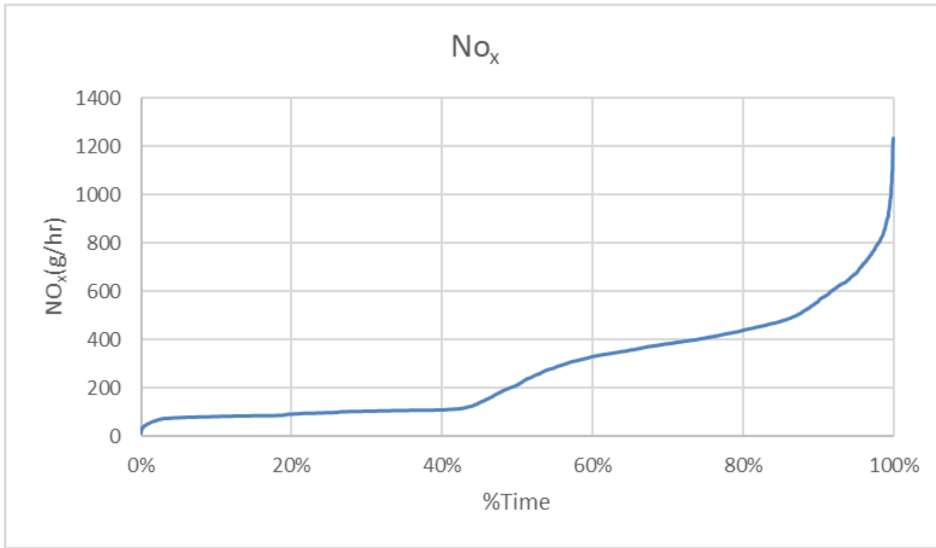


Fig F.26. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Motor Grader 2 (Tier2)

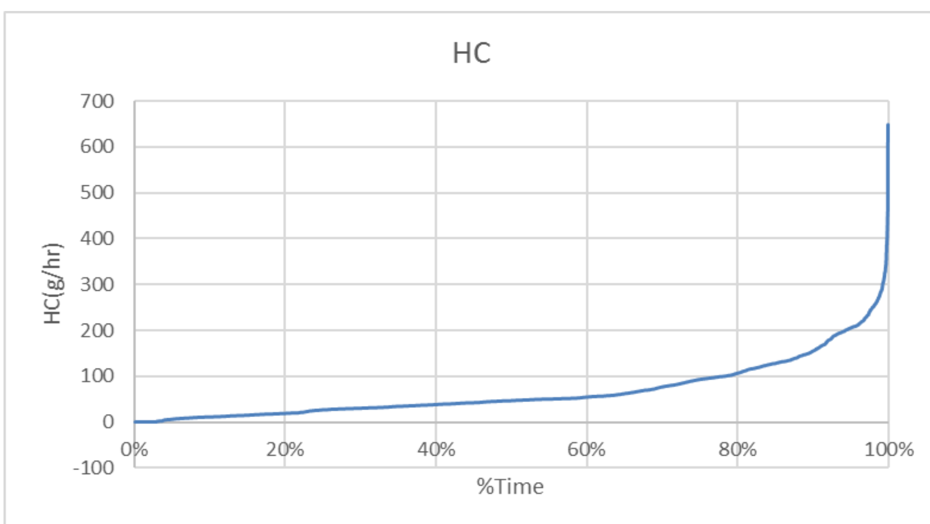


Fig F.27. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Motor Grader 1 (Tier1)

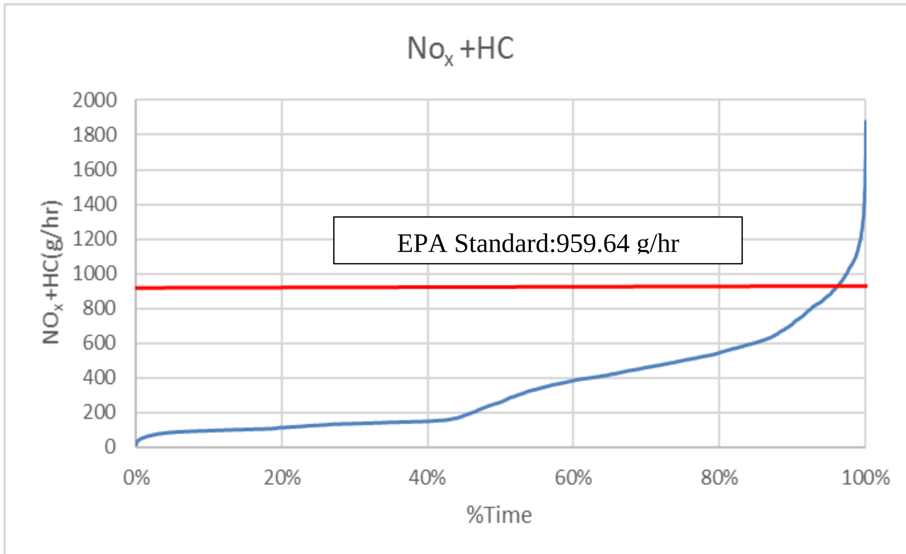


Fig F.28. Cumulative Frequency Diagram (CFD) of NO_x+HC(g/hr) for Motor Grader 1 (Tier1)

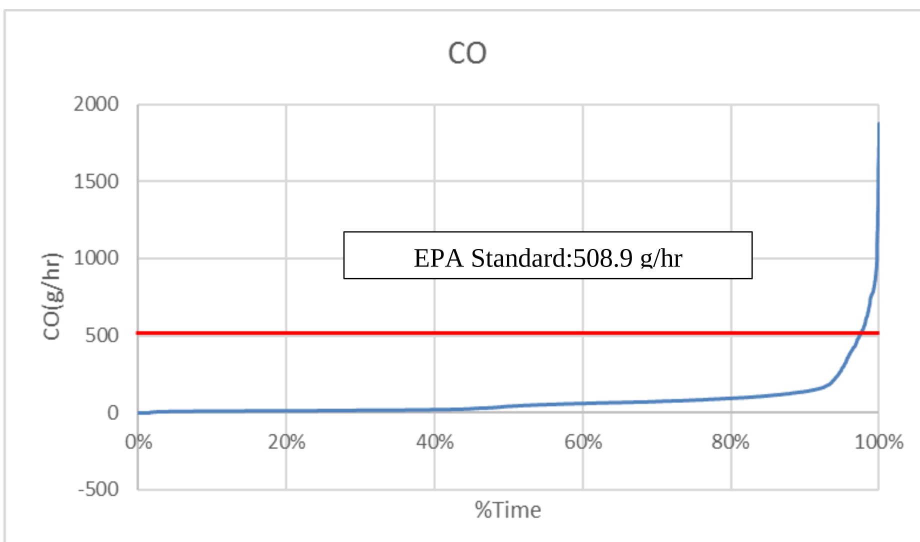


Fig F.29. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Motor Grader 1 (Tier1)

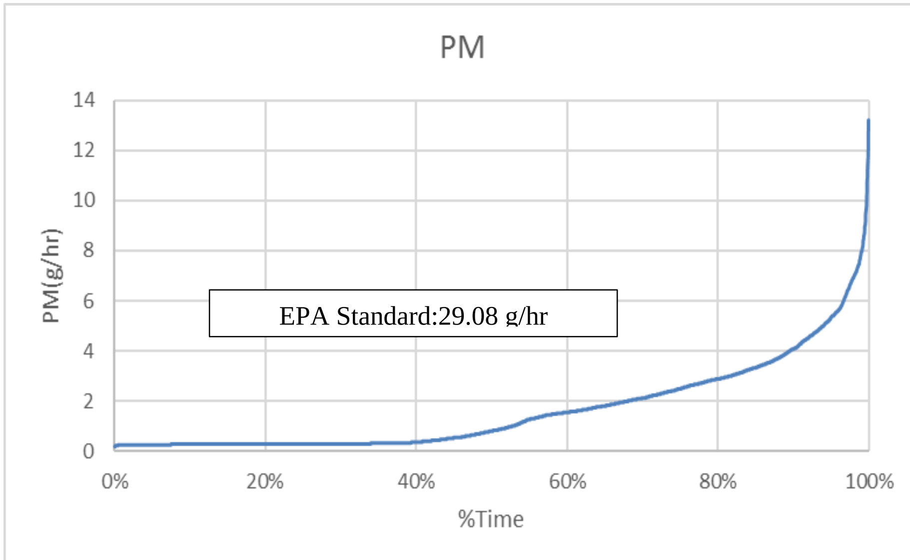


Fig F.30. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Motor Grader 1 (Tier1)

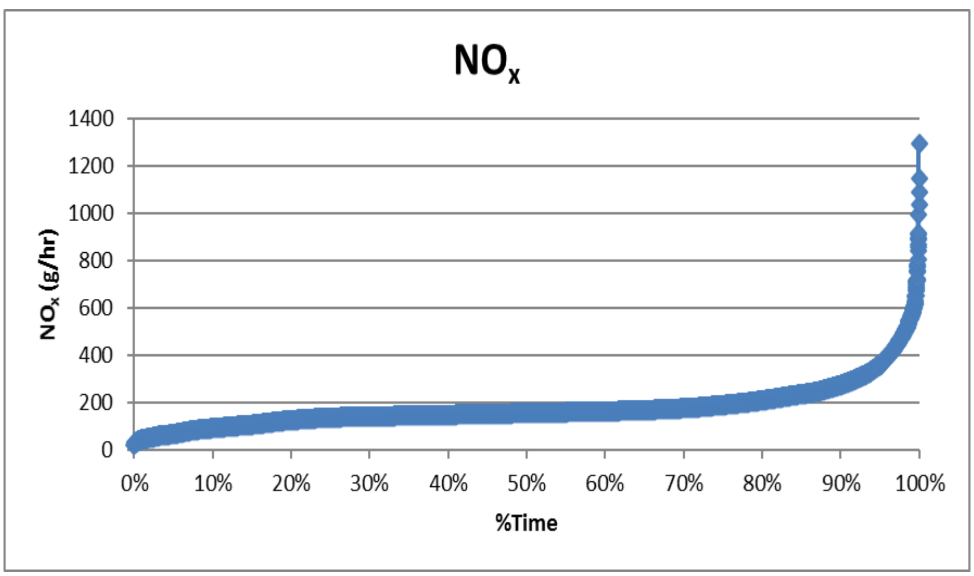


Fig F.31. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Motor Grader 6 (Tier3)

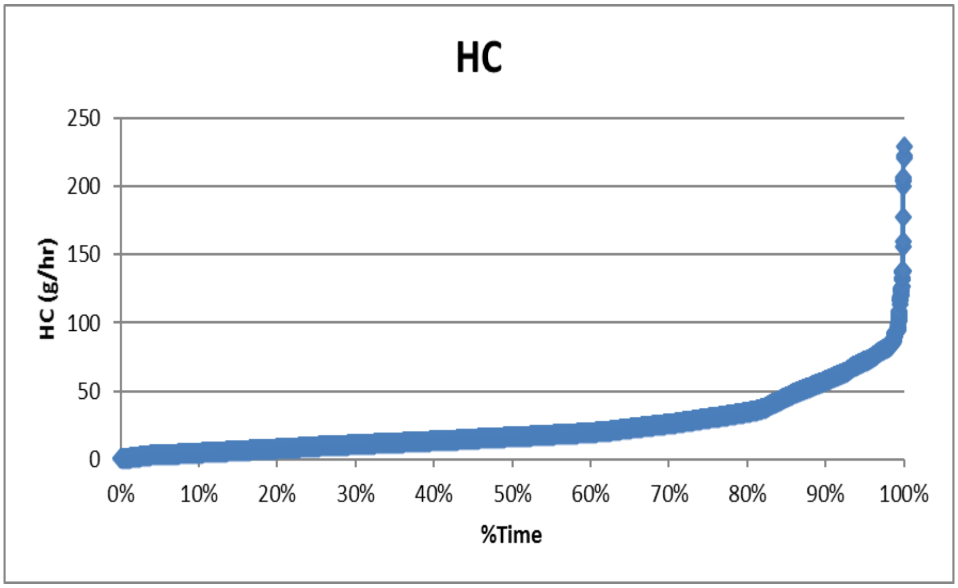


Fig F.32. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Motor Grader 6 (Tier3)

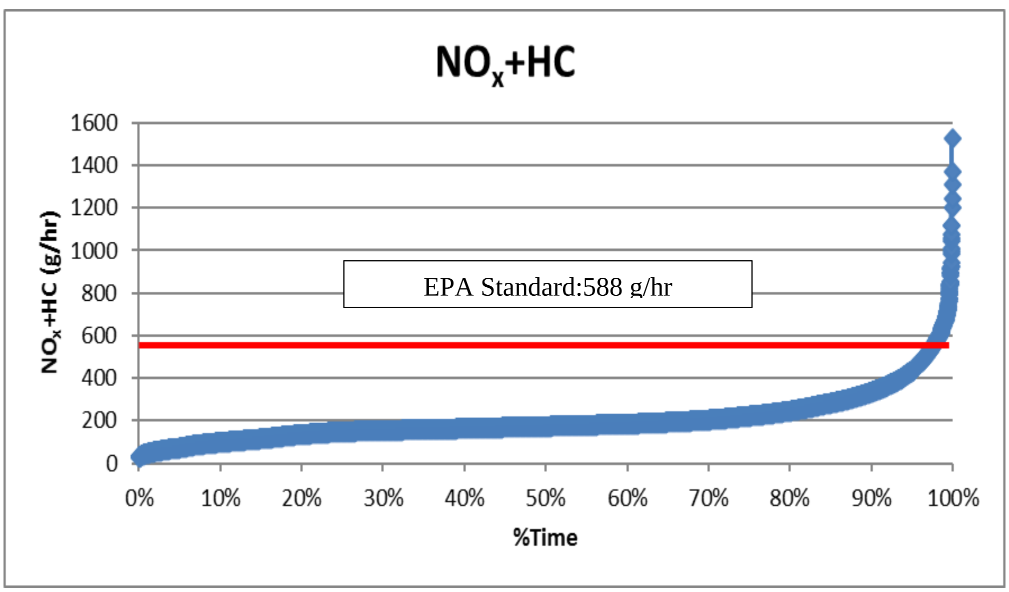


Fig F.33. Cumulative Frequency Diagram (CFD) of NO_x+HC(g/hr) for Motor Grader 6 (Tier3)

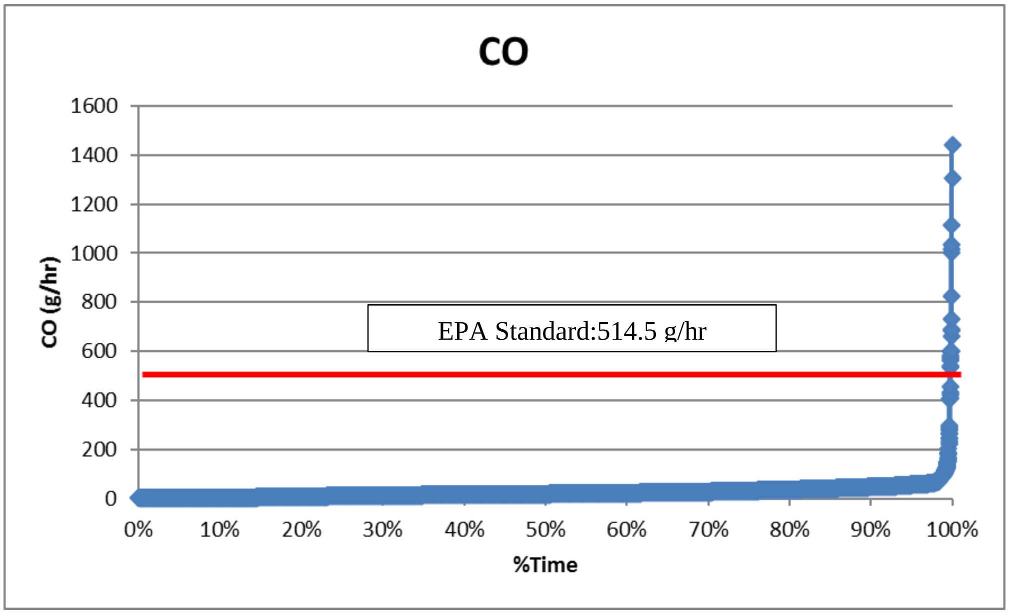


Fig F.34. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Motor Grader 6 (Tier3)

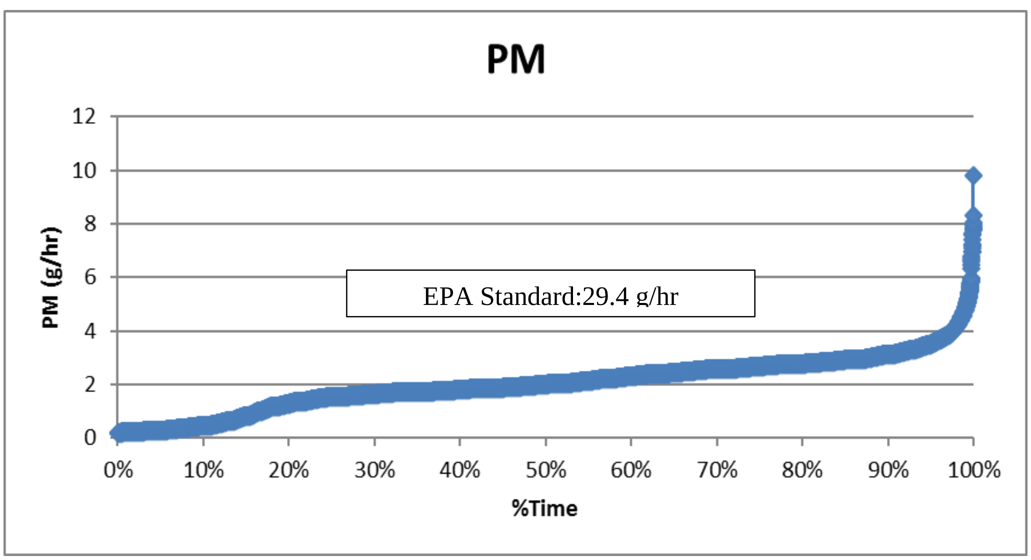


Fig F.35. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Motor Grader 6 (Tier3)

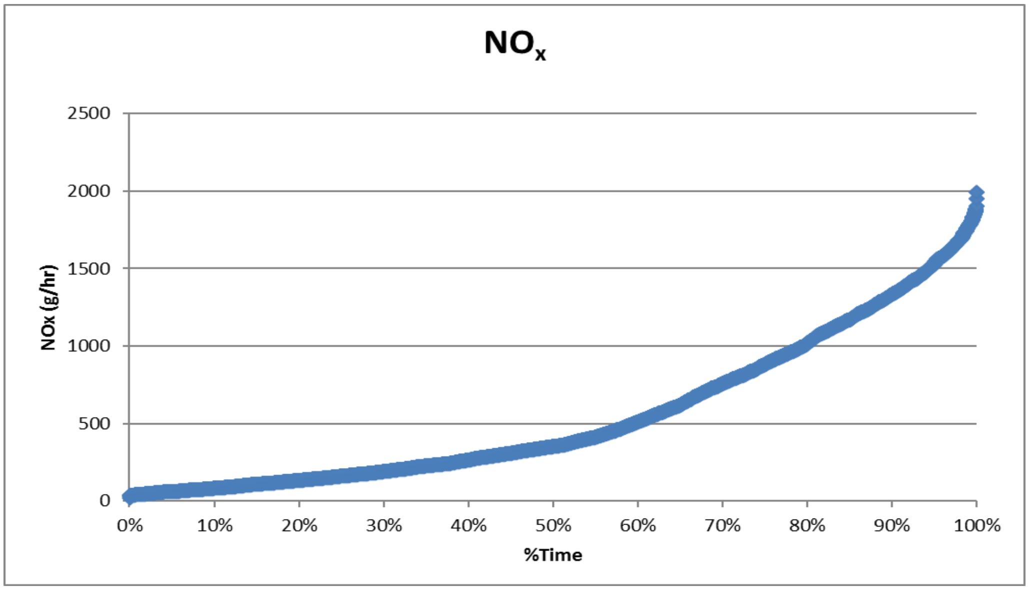


Fig F.36. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Track Loader 2 (Tier0)

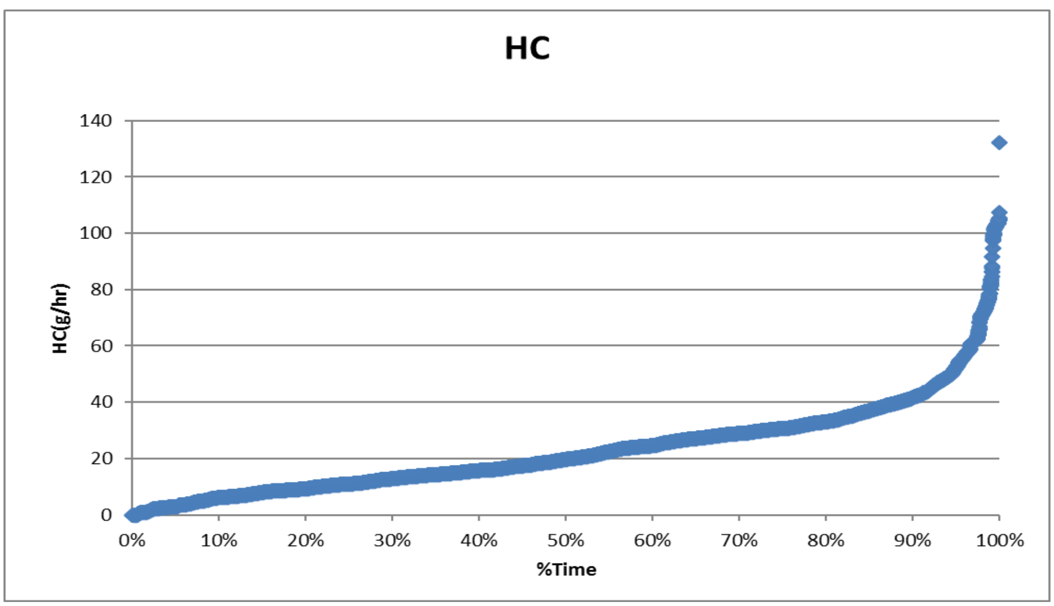


Fig F.37. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Track Loader 2 (Tier0)

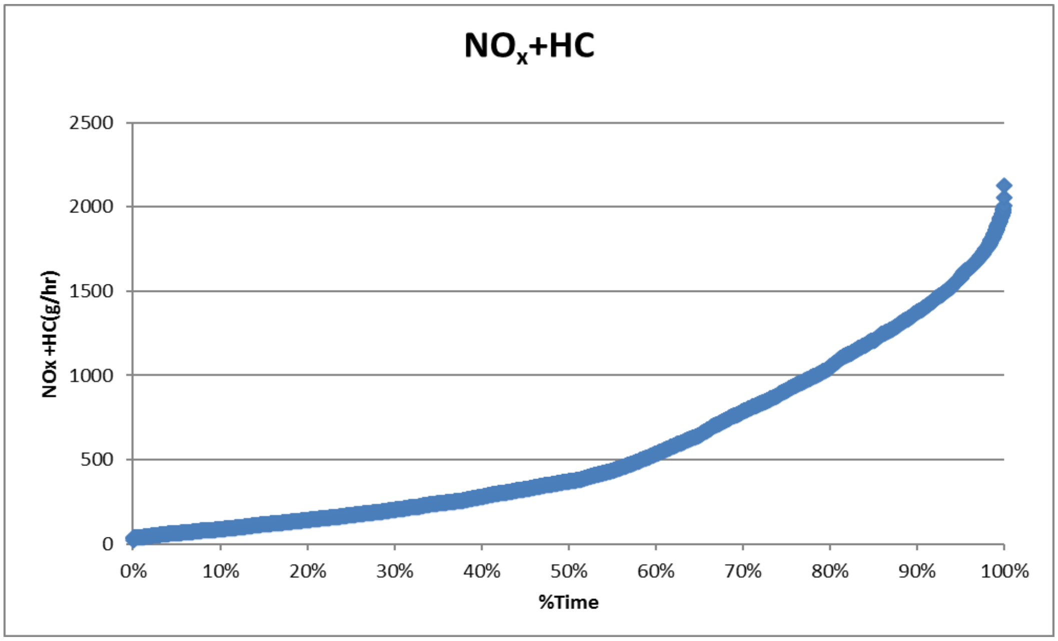


Fig F.38. Cumulative Frequency Diagram (CFD) of NO_x+HC(g/hr) for Track Loader 2 (Tier0)

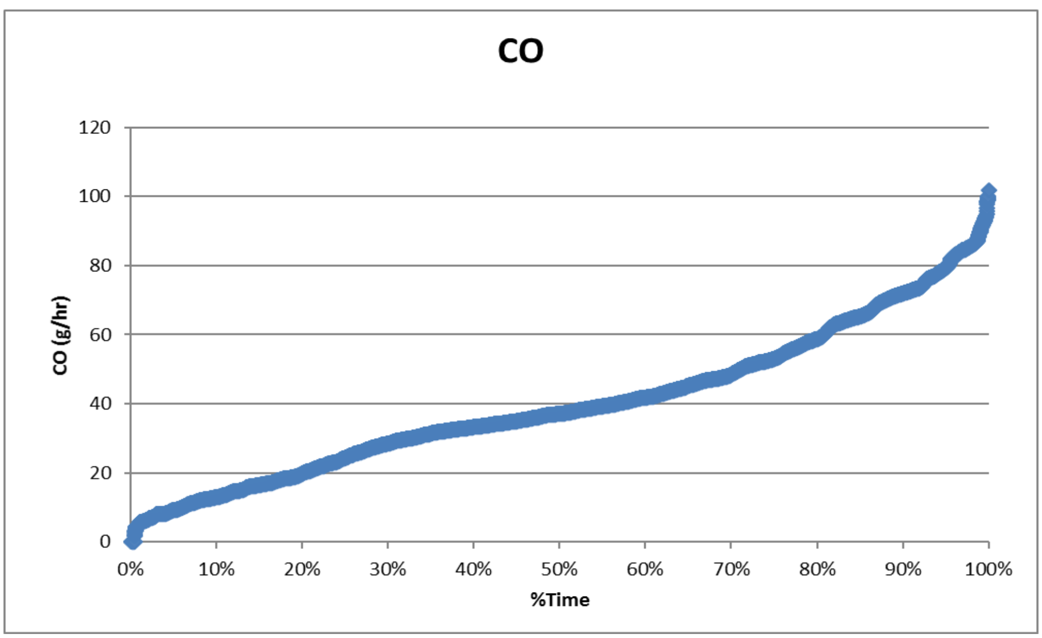


Fig F.39. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Track Loader 2 (Tier0)

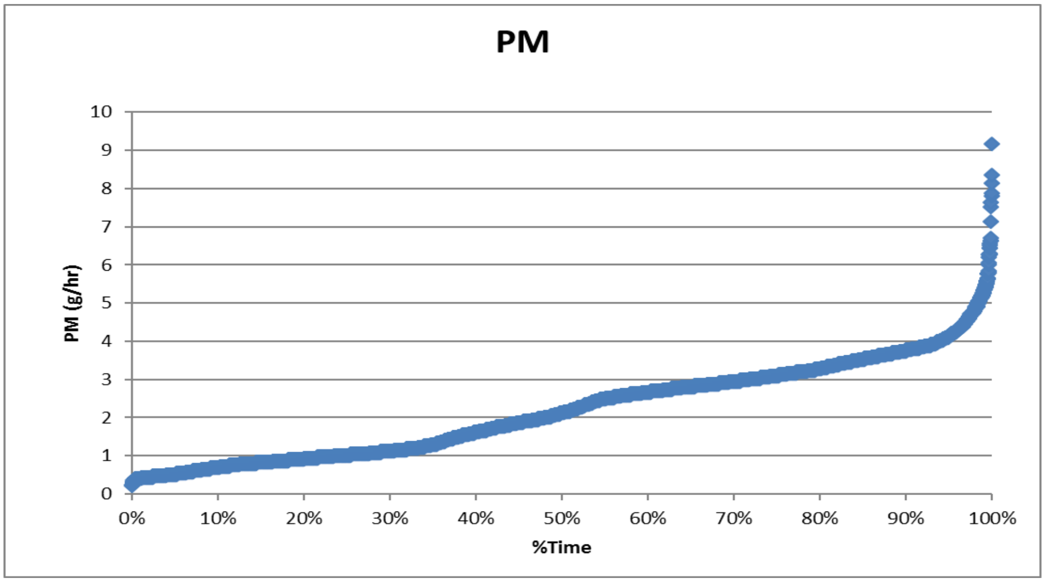


Fig F.40. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Track Loader 2 (Tier0)

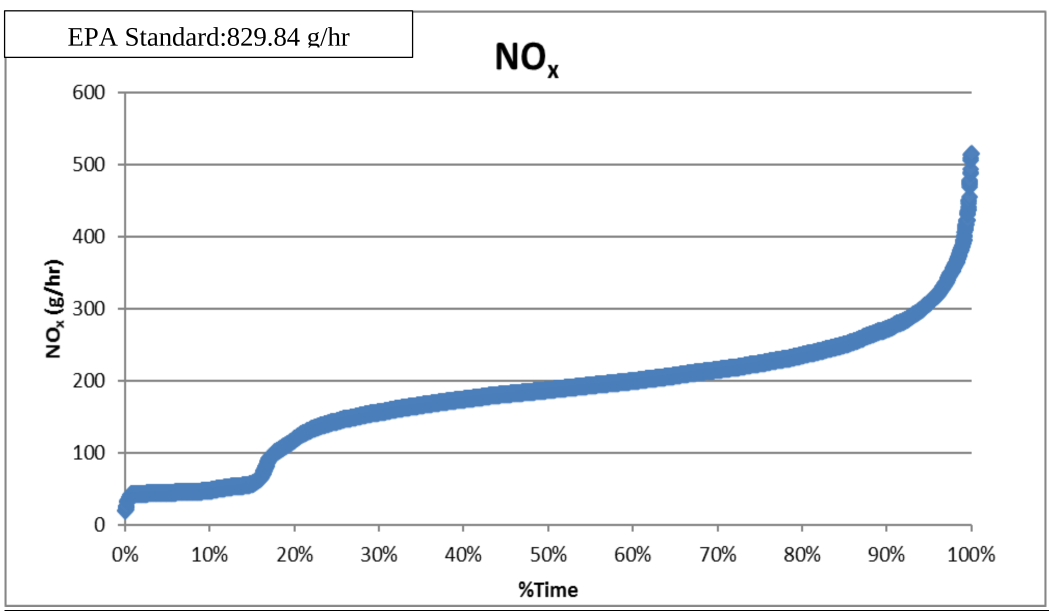


Fig F.41. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Track Loader 1 (Tier1)

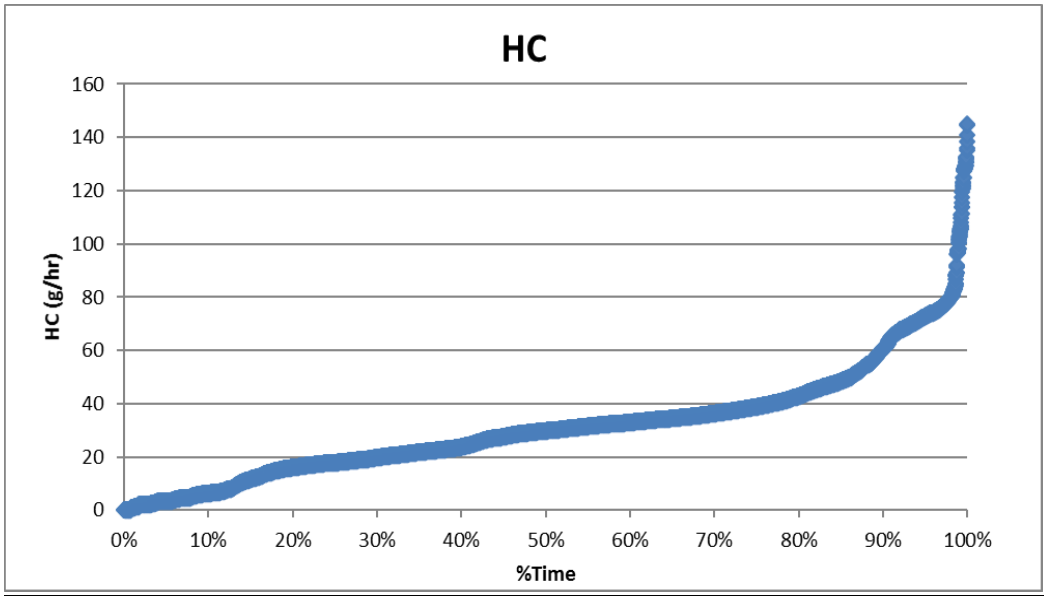


Fig F.42. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Track Loader 1 (Tier1)

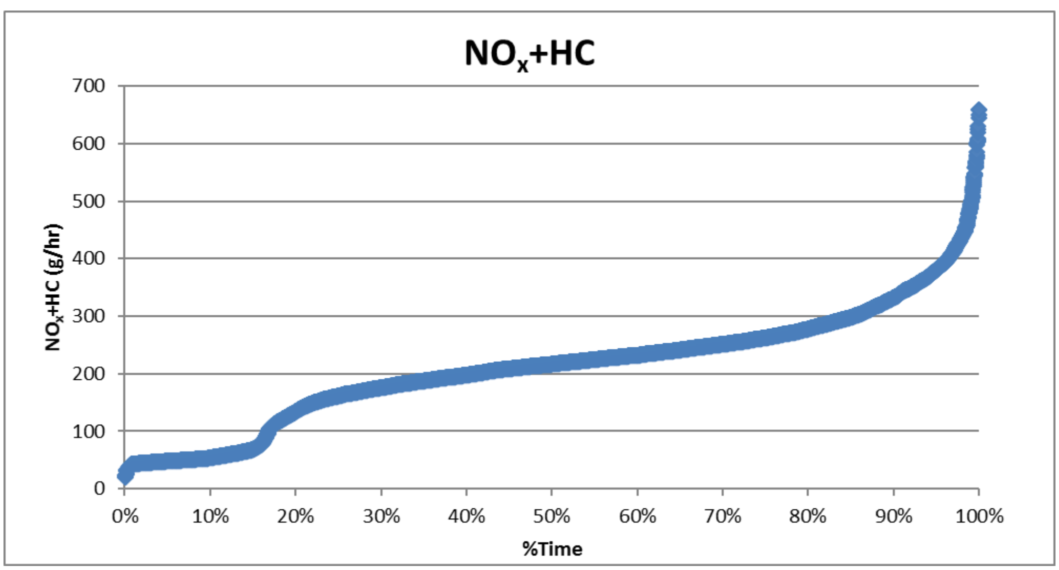


Fig F.43. Cumulative Frequency Diagram (CFD) of NO_x+HC(g/hr) for Track Loader 1 (Tier1)

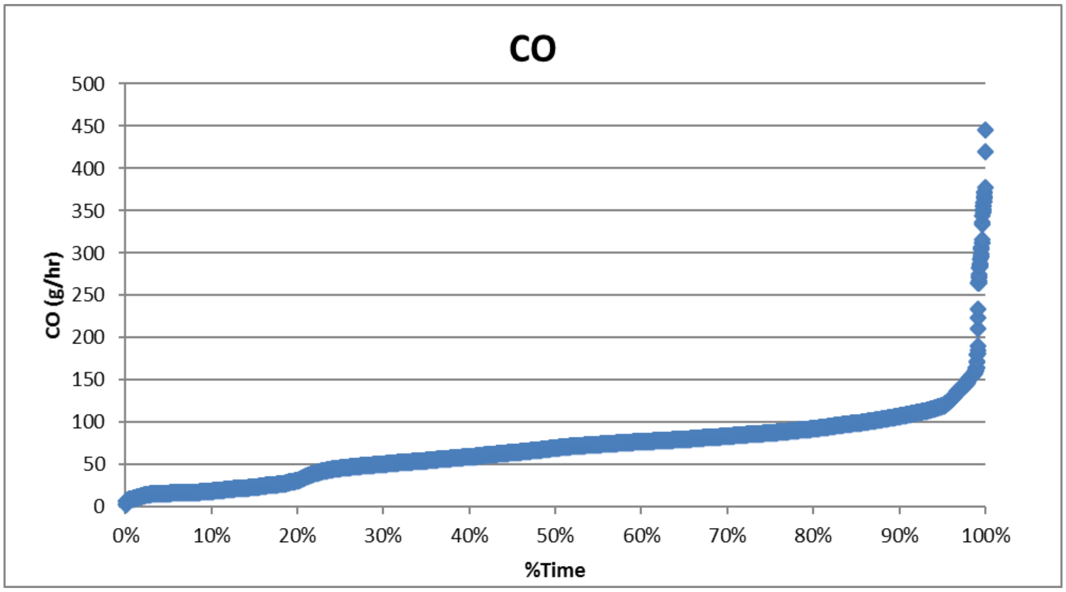


Fig F.44. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Track Loader 1 (Tier1)

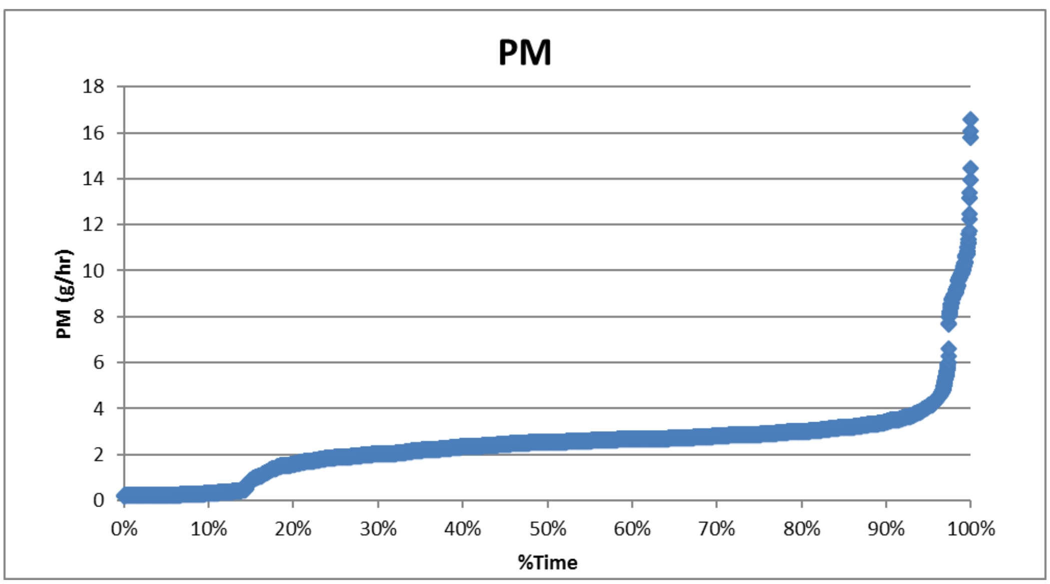


Fig F.45. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Track Loader 1 (Tier1)

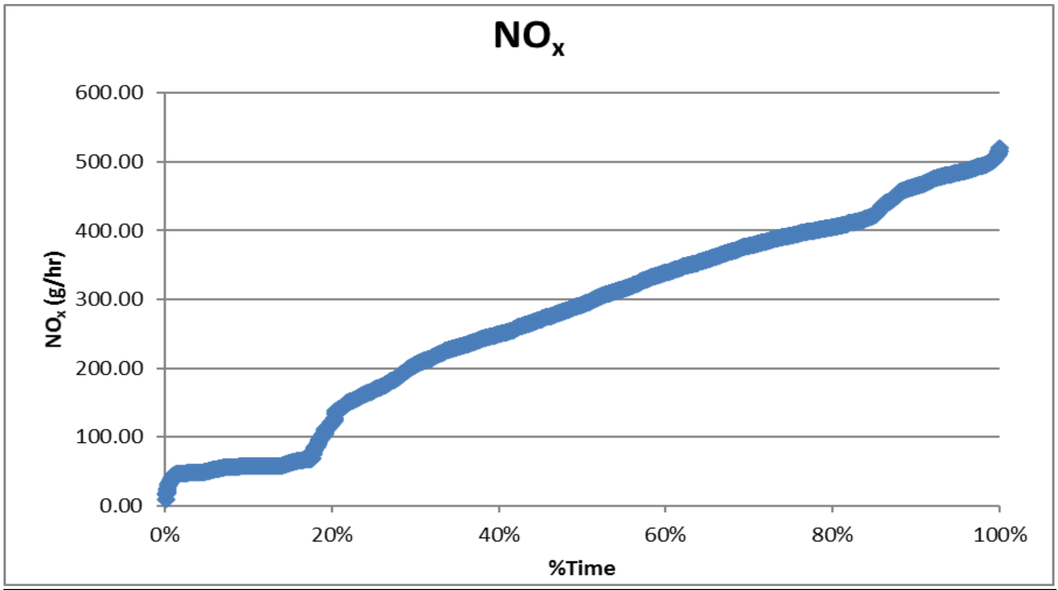


Fig F.46. Cumulative Frequency Diagram (CFD) of NO_x(g/hr) for Track Loader 3 (Tier2)

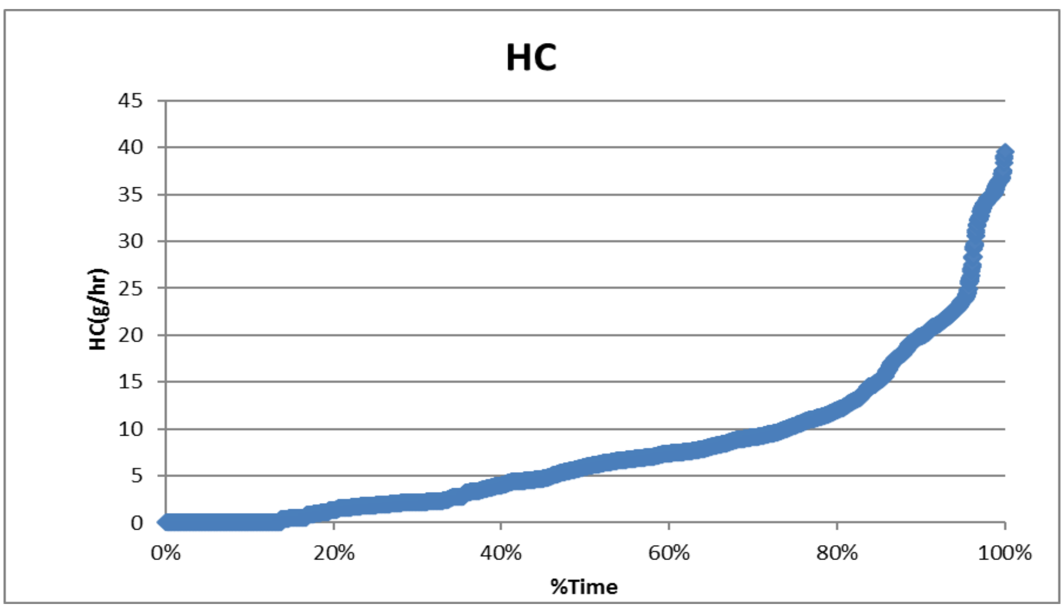


Fig F.47. Cumulative Frequency Diagram (CFD) of HC(g/hr) for Track Loader 3 (Tier2)

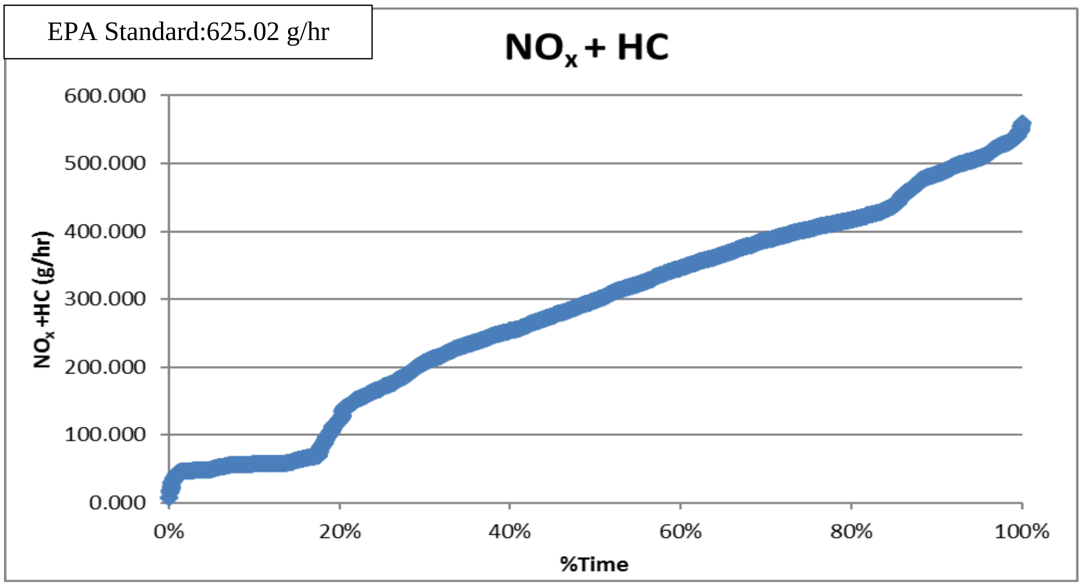


Fig F.48. Cumulative Frequency Diagram (CFD) of NO_x+HC(g/hr) for Track Loader 3 (Tier 2)

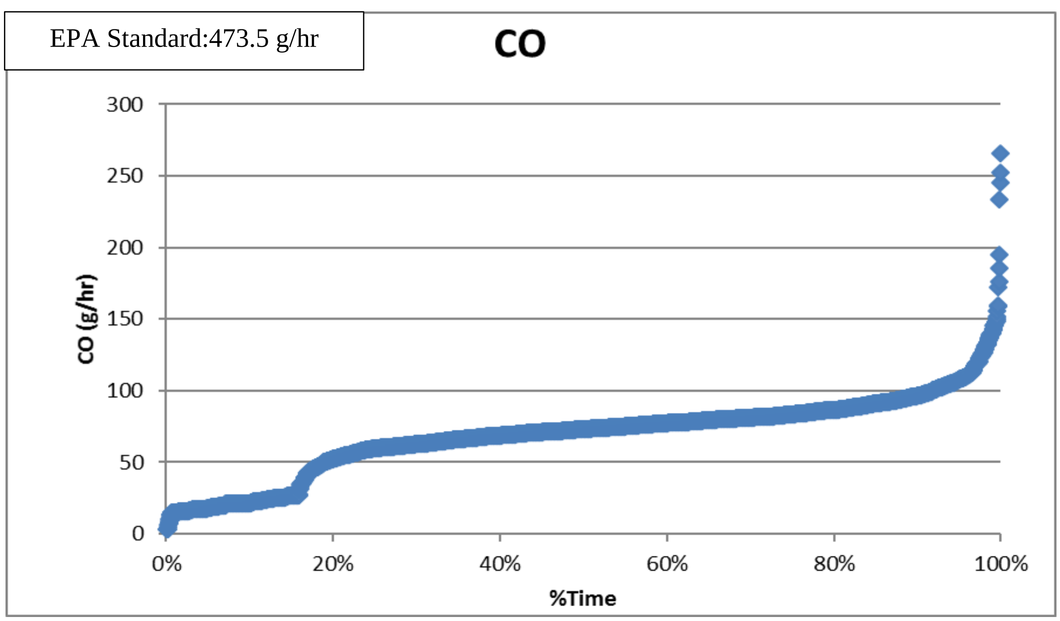


Fig F.49. Cumulative Frequency Diagram (CFD) of CO(g/hr) for Track Loader 3 (Tier2)

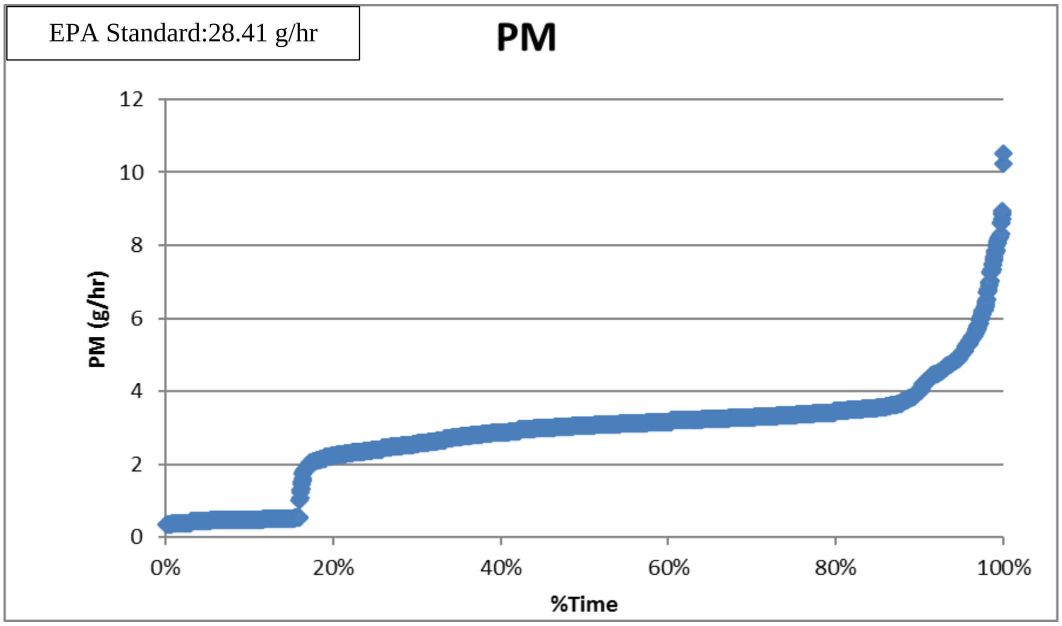


Fig F.50. Cumulative Frequency Diagram (CFD) of PM(g/hr) for Track Loader 3 (Tier2)

Appendix G

One-Way ANOVA-Tukey Test Results for Dozers

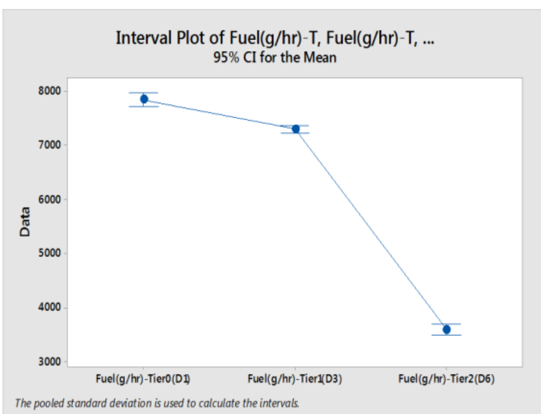
<u>Fuel (g/hr)</u>

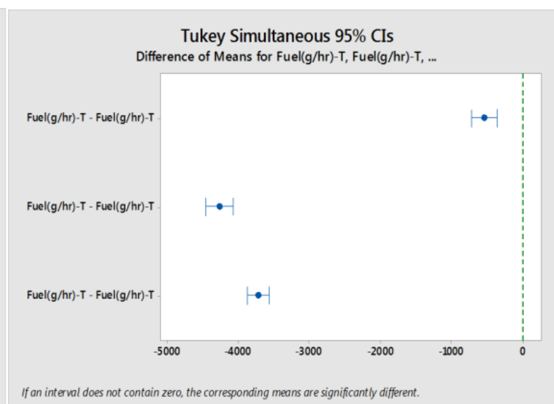
Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
Fuel(g/hr)-Tier0(D1)	3011	7850.4	A
Fuel(g/hr)-Tier1(D3)	9462	7306.1	B
Fuel(g/hr)-Tier2(D6)	5085	3584.5	C

Means that do not share a letter are significantly different.





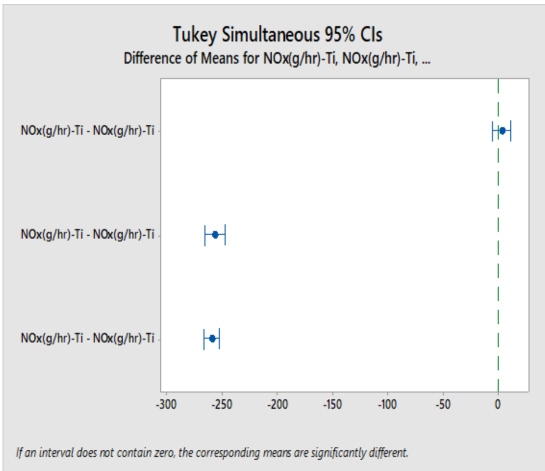
<u>NO_x (g/hr)</u>

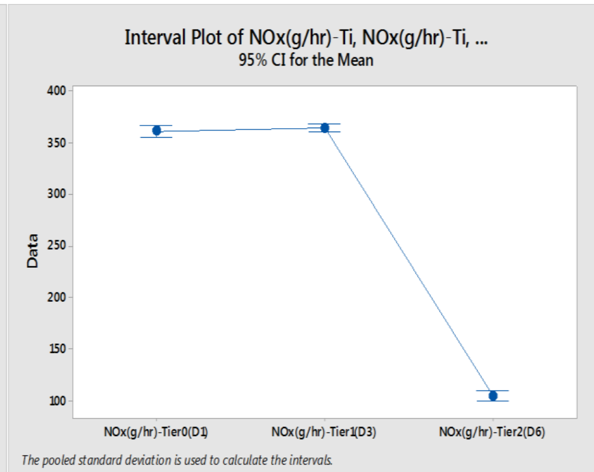
Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
NO_x(g/hr)-Tier1(D3)	9462	364.06	A
NO_x(g/hr)-Tier0(D1)	3011	360.85	A
NO_x(g/hr)-Tier2(D6)	5085	104.166	B

Means that do not share a letter are significantly different.



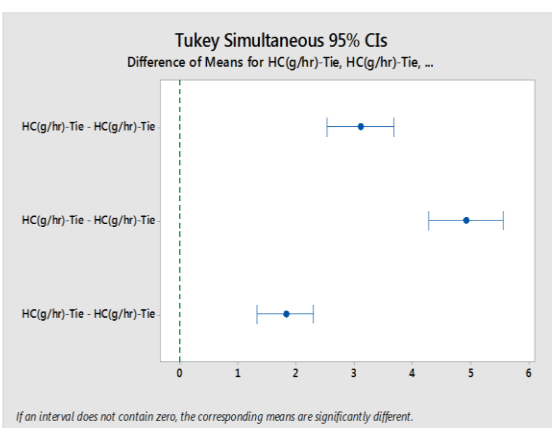


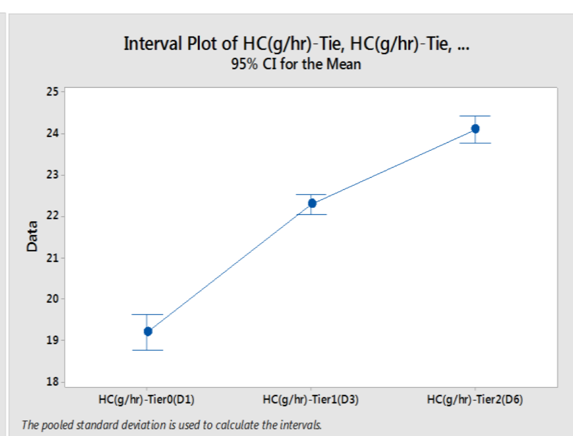
<u>HC(g/hr)</u>

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping		
HC(g/hr)-Tier2(D6)	5085	24.104	A		
HC(g/hr)-Tier1(D3)	9462	22.2955		B	
HC(g/hr)-Tier0(D1)	3011	19.195			C

Means that do not share a letter are significantly different.



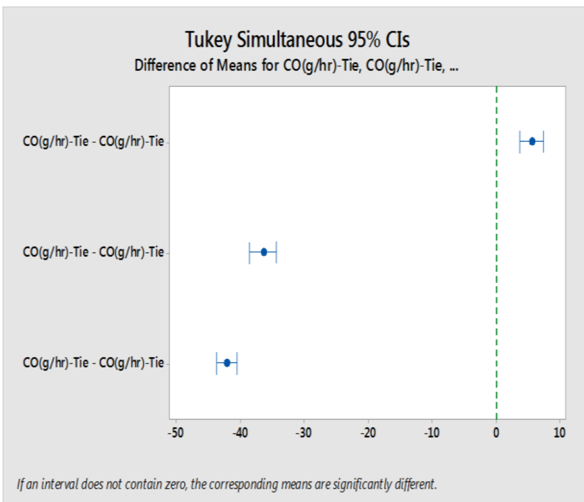


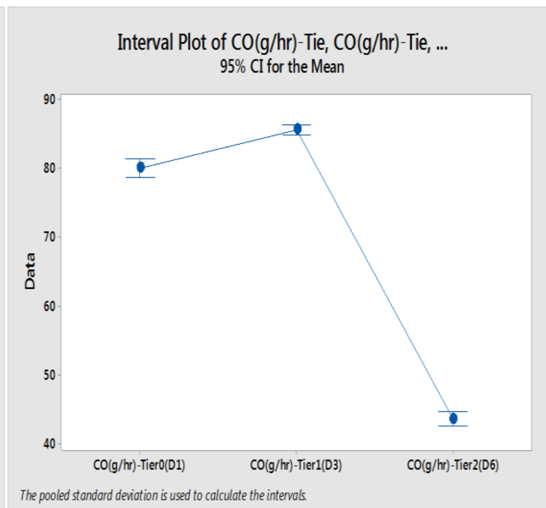
CO(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping		
CO(g/hr)-Tier1(D3)	9462	85.661	A		
CO(g/hr)-Tier0(D1)	3011	80.03		B	
CO(g/hr)-Tier2(D6)	5085	43.524			C

Means that do not share a letter are significantly different.



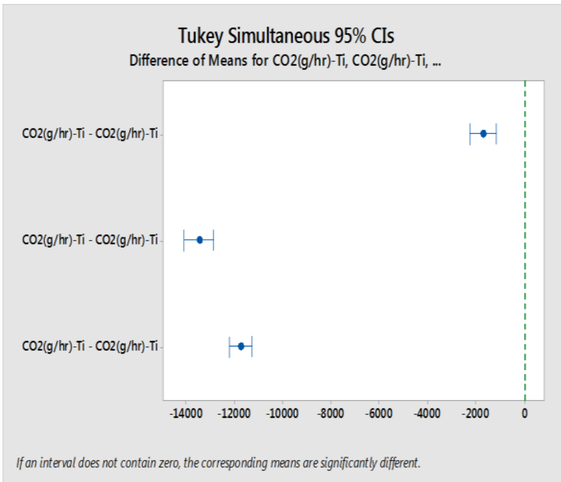


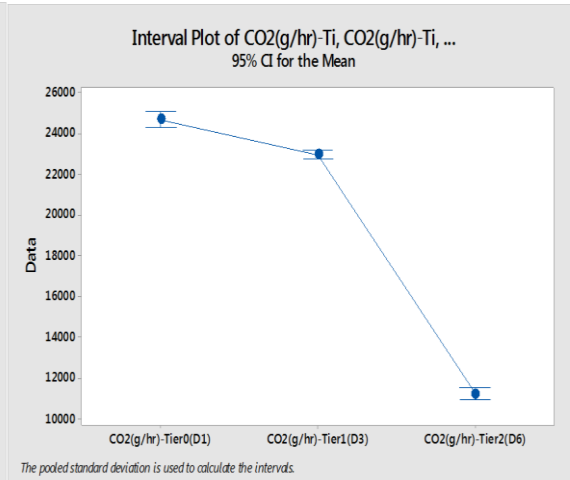
CO_2(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping		
CO_2(g/hr)-Tier0(D1)	3011	24666	A		
CO_2(g/hr)-Tier1(D3)	9462	22943		B	
CO_2(g/hr)-Tier2(D6)	5085	11208.1			C

Means that do not share a letter are significantly different.



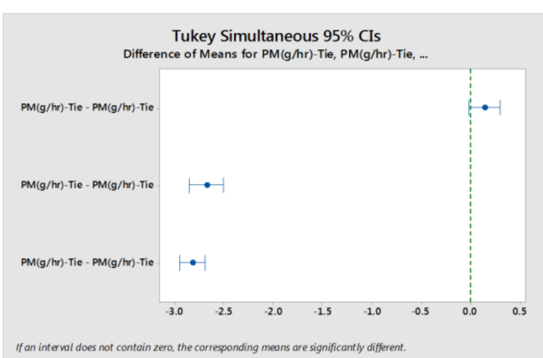


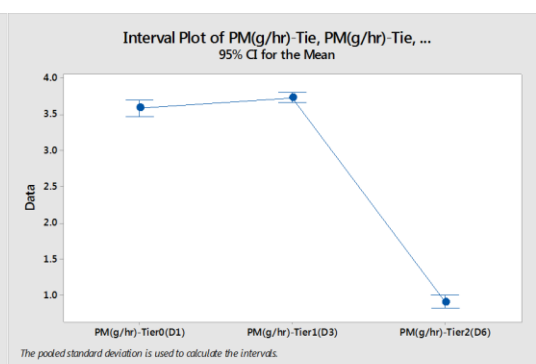
PM(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping	
PM(g/hr)-Tier1(D3)	9462	3.7275	A	
PM(g/hr)-Tier0(D1)	3010	3.5831	A	
PM(g/hr)-Tier2(D6)	5085	0.90518		B

Means that do not share a letter are significantly different.



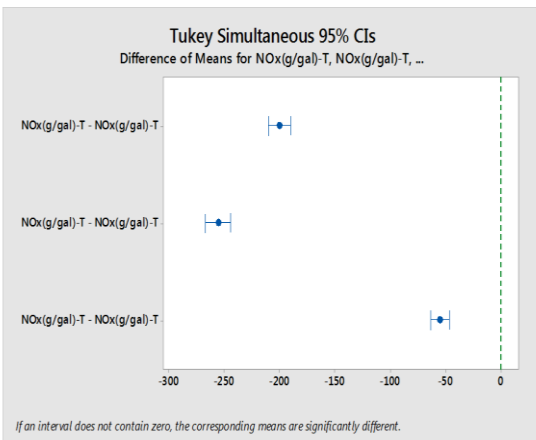


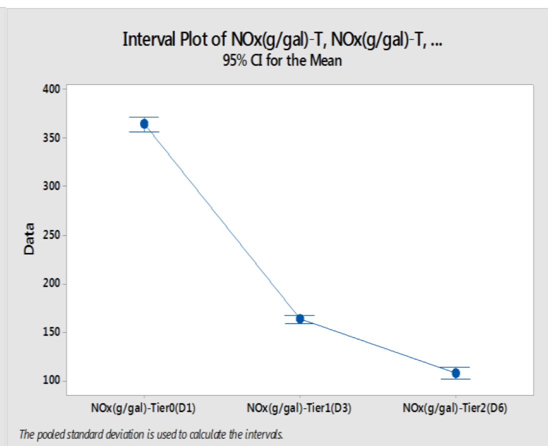
NO_x (g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
NO_x(g/gal)-Tier0(D1)	3011	363.99	A
NO_x(g/gal)-Tier1(D3)	9462	163.352	B
NO_x(g/gal)-Tier2(D6)	5085	107.667	C

Means that do not share a letter are significantly different.





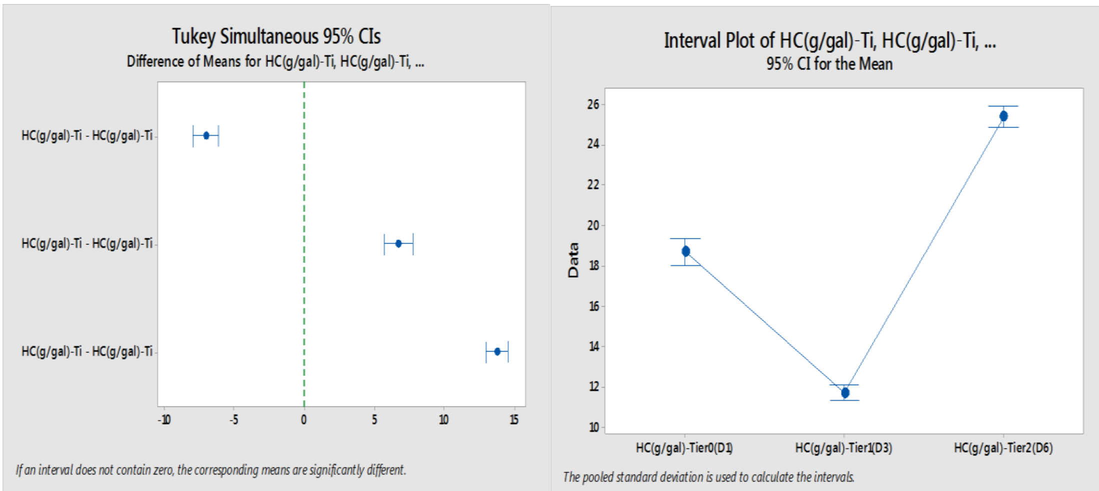
HC(g/gal)

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
HC(g/gal)-Tier2(D6)	5085	25.424	A
HC(g/gal)-Tier0(D1)	3011	18.723	B
HC(g/gal)-Tier1(D3)	9462	11.6881	C

Means that do not share a letter are significantly different.

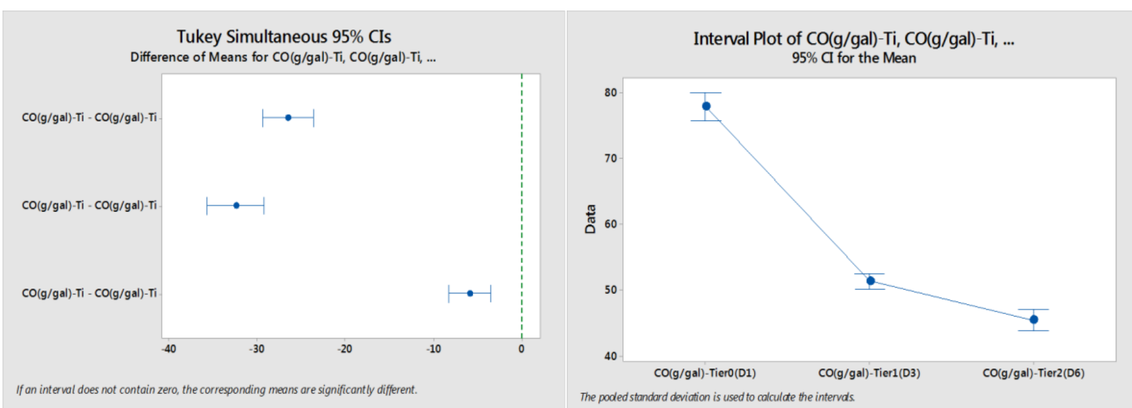


CO(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO(g/gal)-Tier0(D1)	3011	77.92	A
CO(g/gal)-Tier1(D3)	9462	51.435	B
CO(g/gal)-Tier2(D6)	5085	45.473	C

Means that do not share a letter are significantly different.

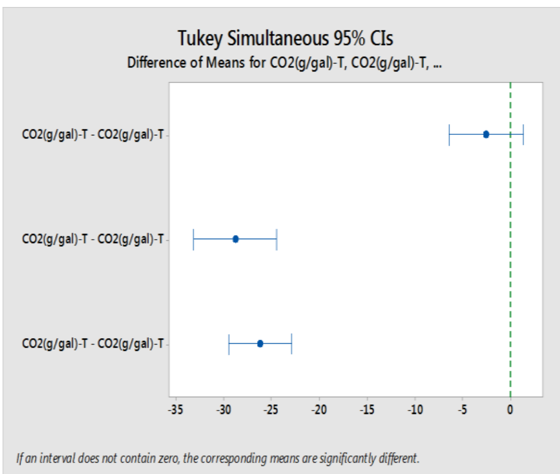


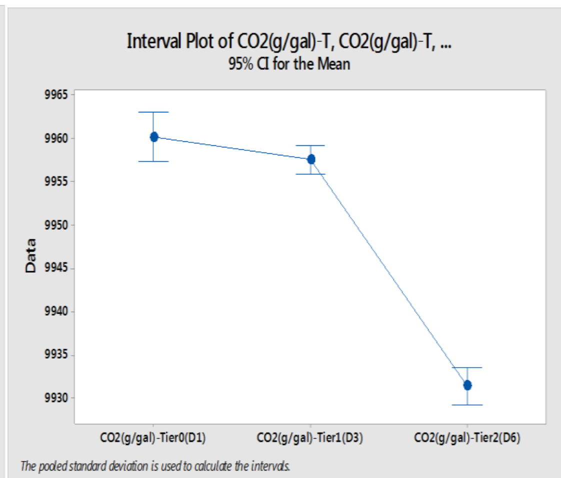
CO_2(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO_2(g/gal)-Tier0(D1)	3011	9960.14	A
CO_2(g/gal)-Tier1(D3)	9462	9957.53	A
CO_2(g/gal)-Tier2(D6)	5085	9931.32	B

Means that do not share a letter are significantly different.



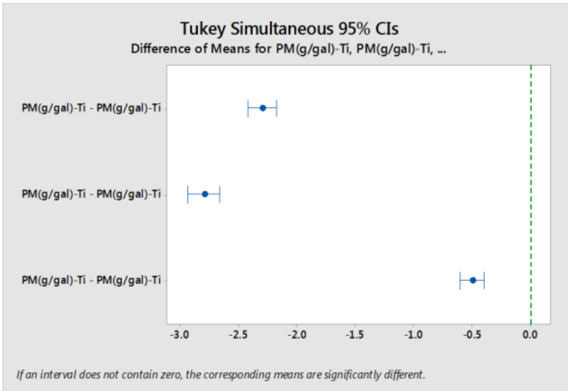
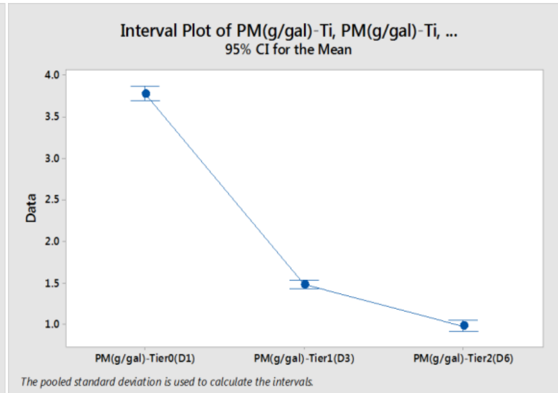


PM(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
PM(g/gal)-Tier0(D1)	3010	3.7808	A
PM(g/gal)-Tier1(D3)	9462	1.4822	B
PM(g/gal)-Tier2(D6)	5085	0.9830	C

Means that do not share a letter are significantly different.


Tukey Simultaneous 95% CIs
Difference of Means for PM(g/gal)-Ti, PM(g/gal)-Ti, ...
PM(g/gal)-Ti - PM(g/gal)-Ti
PM(g/gal)-Ti - PM(g/gal)-Ti
PM(g/gal)-Ti - PM(g/gal)-Ti
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
If an interval does not contain zero, the corresponding means are significantly different.

Interval Plot of PM(g/gal)-Ti, PM(g/gal)-Ti, ...
95% CI for the Mean
Data
4.0
3.5
3.0
2.5
2.0
1.5
1.0
PM(g/gal)-Tier0(D1)
PM(g/gal)-Tier1(D3)
PM(g/gal)-Tier2(D6)
The pooled standard deviation is used to calculate the intervals.

Appendix H

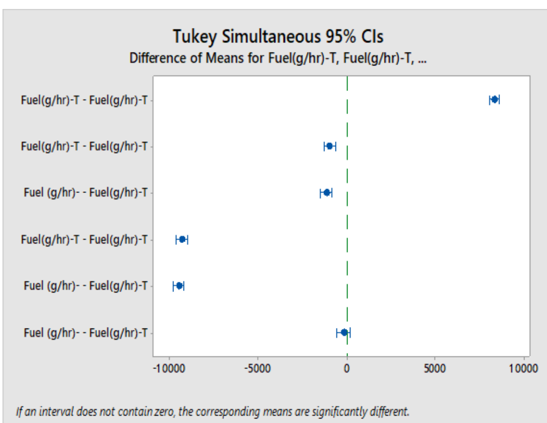
One-Way ANOVA-Tukey Test Results for Motor Graders

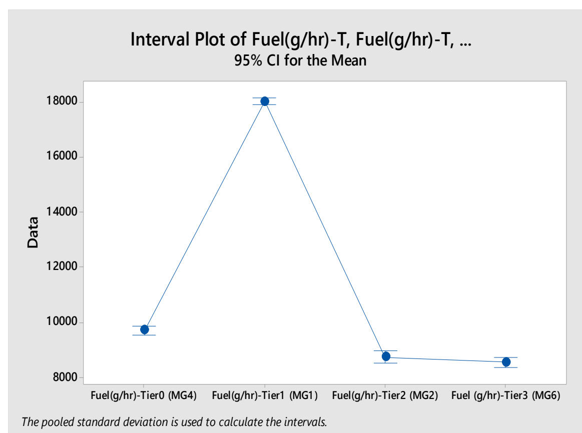
Fuel (g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
Fuel(g/hr)-Tier1(MG1)	15583	18039.0	A
Fuel(g/hr)-Tier0(MG4)	9476	9706.6	B
Fuel(g/hr)-Tier2(MG2)	5503	8735	C
Fuel (g/hr)-Tier3(MG6)	7094	8537.6	C

Means that do not share a letter are significantly different.



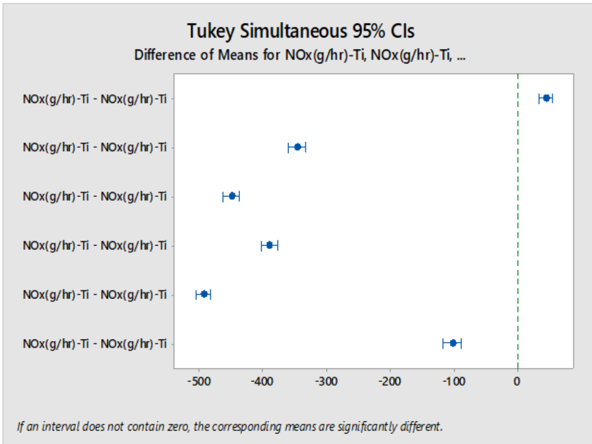


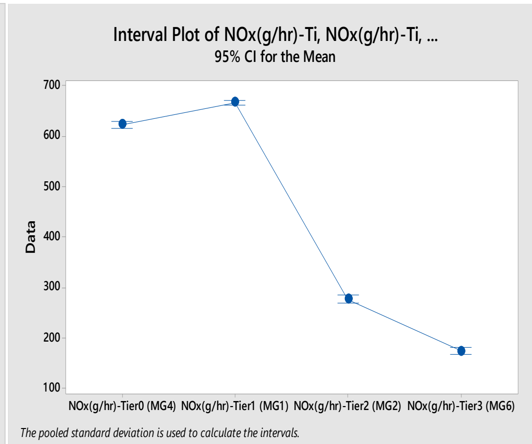
NO_x (g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
NO_x(g/hr)-Tier1(MG1)	15583	667.41	A
NO_x(g/hr)-Tier0(MG4)	9476	623.76	B
NO_x(g/hr)-Tier2(MG2)	5503	276.98	C
NO_x(g/hr)-Tier3(MG6)	7094	173.80	D

Means that do not share a letter are significantly different.



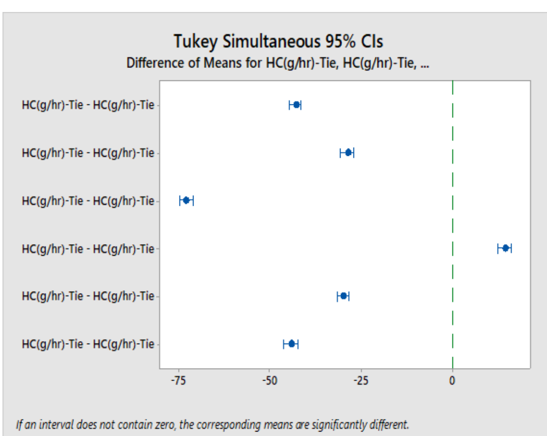


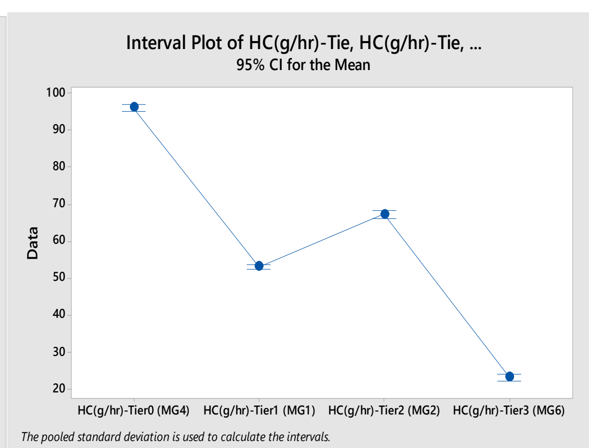
HC(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
HC(g/hr)-Tier0 (MG4)	9476	96.159	A
HC(g/hr)-Tier2 (MG2)	5503	67.283	B
HC(g/hr)-Tier1 (MG1)	15582	53.060	C
HC(g/hr)-Tier3 (MG6)	7094	23.070	D

Means that do not share a letter are significantly different.



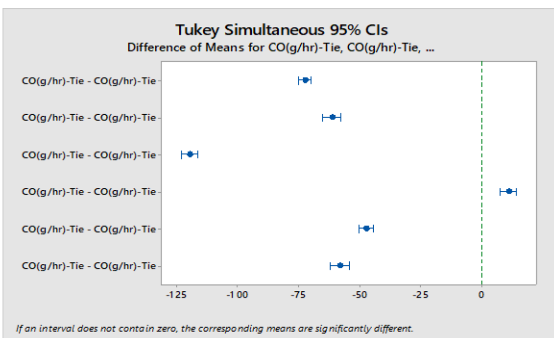


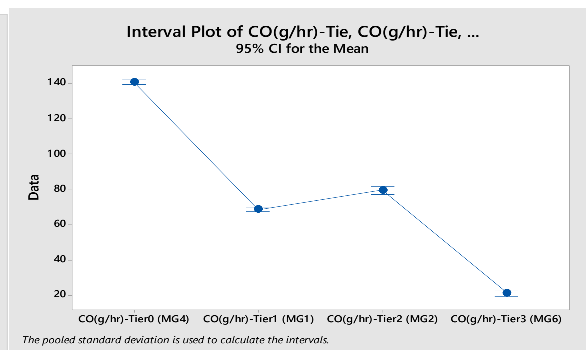
CO(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO(g/hr)-Tier0 (MG4)	9476	141.010	A
CO(g/hr)-Tier2 (MG2)	5503	79.42	B
CO(g/hr)-Tier1 (MG1)	15582	68.479	C
CO(g/hr)-Tier3 (MG6)	7094	21.106	D

Means that do not share a letter are significantly different.



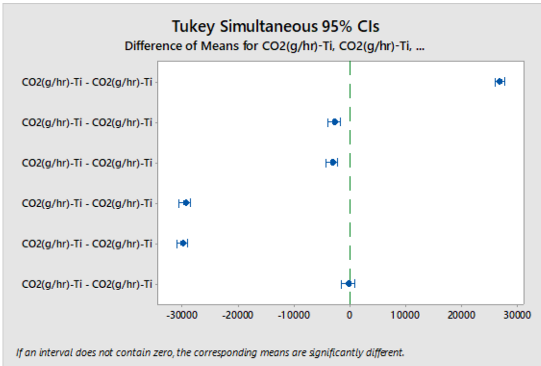


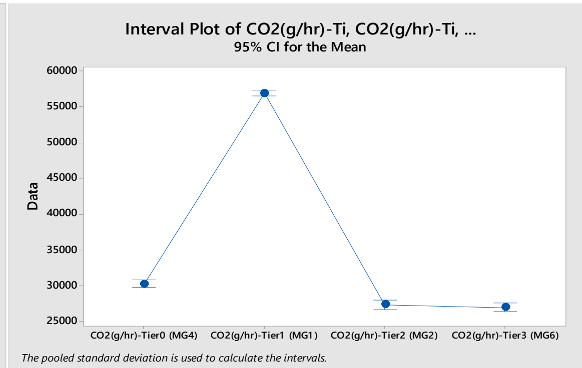
CO_2(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO_2(g/hr)-Tier1 (MG1)	15582	56855	A
CO_2(g/hr)-Tier0 (MG4)	9476	30211	B
CO_2(g/hr)-Tier2 (MG2)	5503	27332	C
CO_2(g/hr)-Tier3 (MG6)	7094	26925	C

Means that do not share a letter are significantly different.



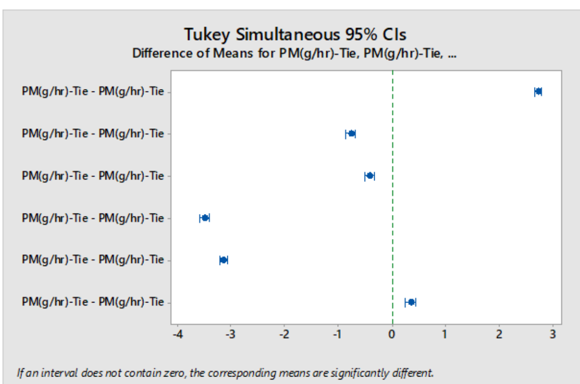


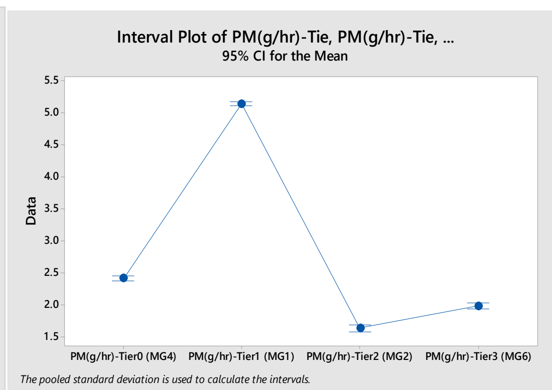
PM(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
PM(g/hr)-Tier1 (MG1)	15582	5.1402	A
PM(g/hr)-Tier0 (MG4)	9476	2.4126	B
PM(g/hr)-Tier3 (MG6)	7094	1.9843	C
PM(g/hr)-Tier2 (MG2)	5503	1.6388	D

Means that do not share a letter are significantly different.



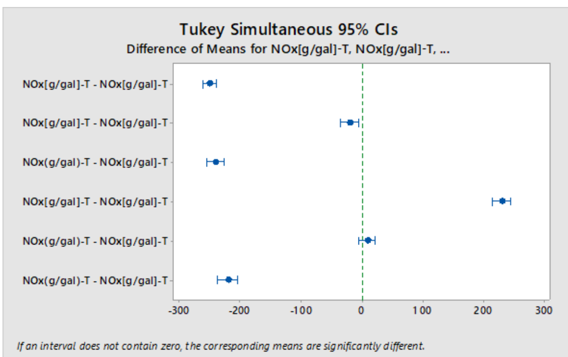


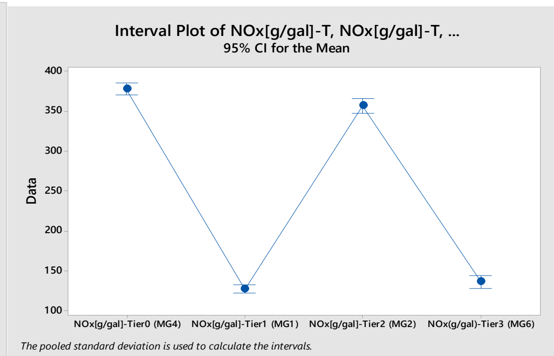
NO_x(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
NO_x[g/gal]-Tier0 (MG4)	9476	377.37	A
NO_x[g/gal]-Tier2 (MG2)	5503	356.51	B
NO_x(g/gal)-Tier3 (MG6)	7094	135.79	C
NO_x[g/gal]-Tier1 (MG1)	15582	126.943	C

Means that do not share a letter are significantly different.



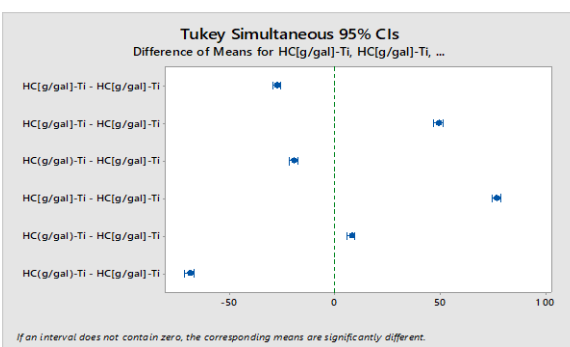


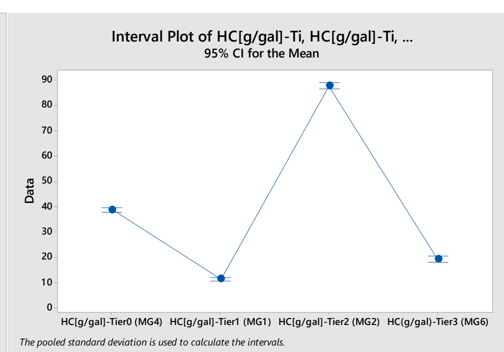
HC(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
HC[g/gal]-Tier2 (MG2)	5503	87.95	A
HC[g/gal]-Tier0 (MG4)	9476	38.820	B
HC(g/gal)-Tier3 (MG6)	7094	19.239	C
HC[g/gal]-Tier1 (MG1)	15582	11.3866	D

Means that do not share a letter are significantly different.



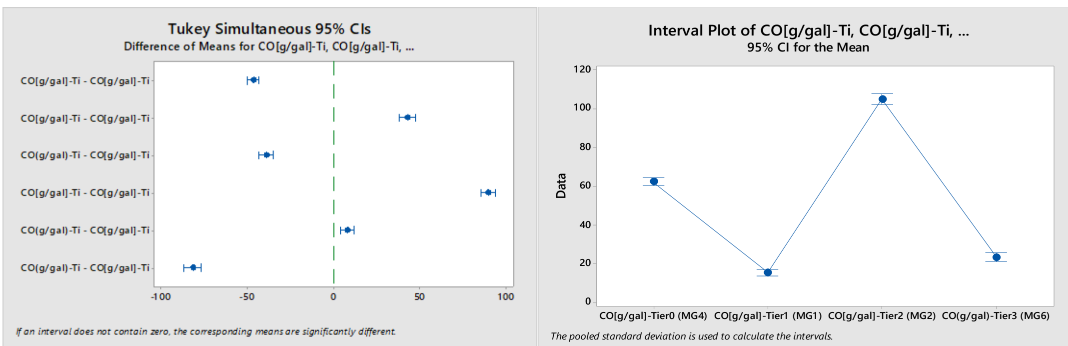


CO(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO[g/gal]-Tier2 (MG2)	5503	104.96	A
CO[g/gal]-Tier0 (MG4)	9476	62.205	B
CO(g/gal)-Tier3 (MG6)	7094	23.23	C
CO[g/gal]-Tier1 (MG1)	15582	15.4259	D

Means that do not share a letter are significantly different.

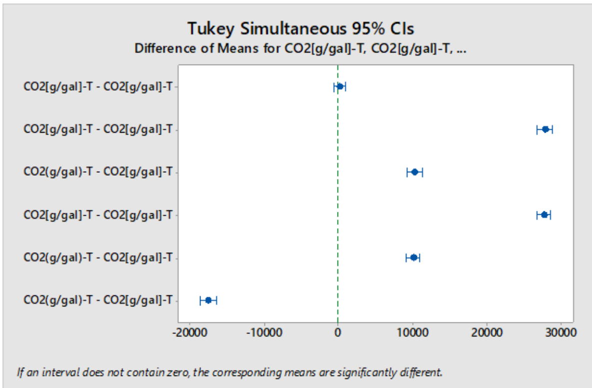


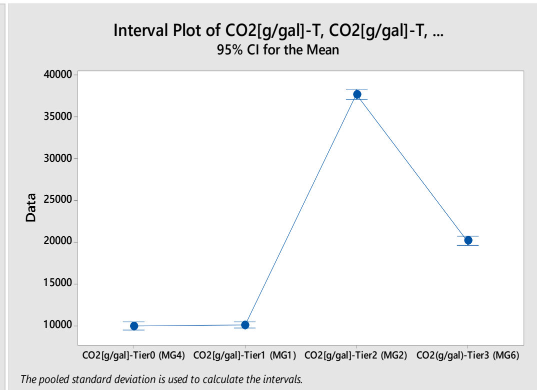
CO_2(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO_2[g/gal]-Tier2 (MG2)	5503	37663	A
CO_2(g/gal)-Tier3 (MG6)	7094	20076	B
CO_2[g/gal]-Tier1 (MG1)	15582	10009.7	C
CO_2[g/gal]-Tier0 (MG4)	9476	9849.66	C

Means that do not share a letter are significantly different.



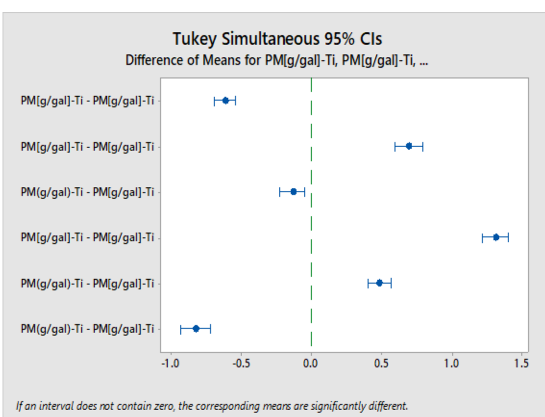


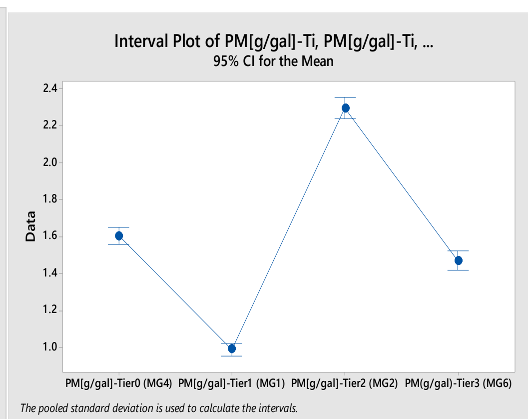
PM(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
PM[g/gal]-Tier2 (MG2)	5503	2.2969	A
PM[g/gal]-Tier0 (MG4)	9476	1.6046	B
PM(g/gal)-Tier3 (MG6)	7094	1.4684	C
PM[g/gal]-Tier1 (MG1)	15582	0.98724	D

Means that do not share a letter are significantly different.





Appendix I

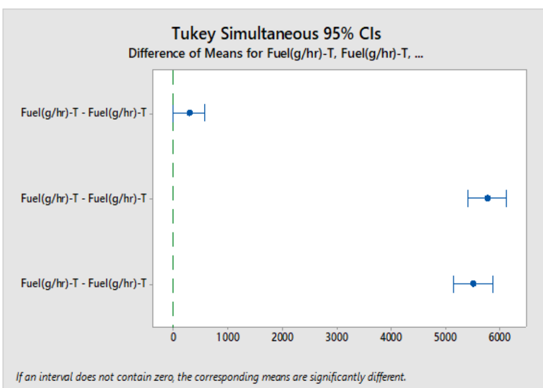
One-Way ANOVA-Tukey Test Results for Track Loaders

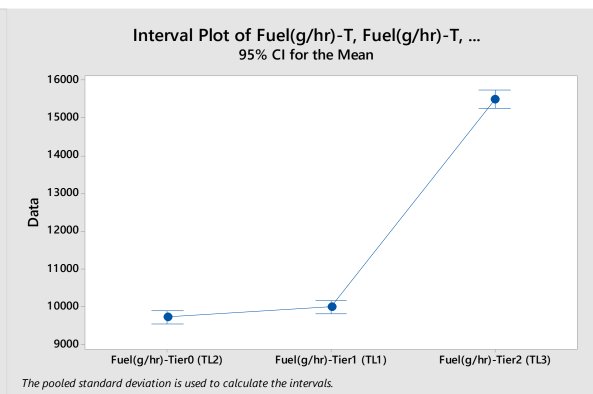
Fuel (g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping	
Fuel(g/hr)-Tier2 (TL3)	2416	15491	A	
Fuel(g/hr)-Tier1 (TL1)	5046	9988.6		B
Fuel(g/hr)-Tier0 (TL2)	4850	9720.7		B

Means that do not share a letter are significantly different.



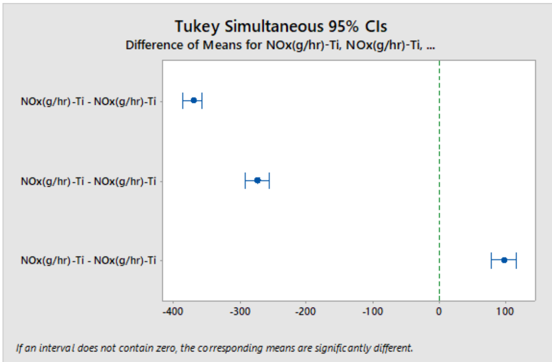


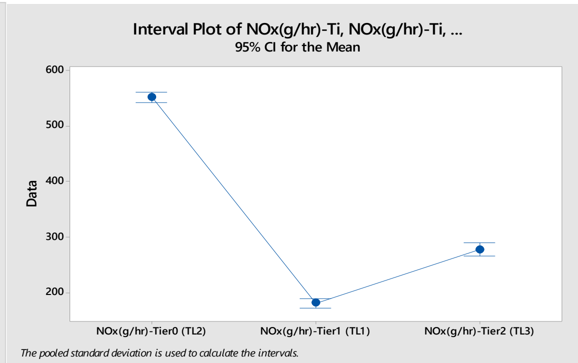
NO_x (g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping		
NO_x(g/hr)-Tier0 (TL2)	4850	551.63	A		
NO_x(g/hr)-Tier2 (TL3)	2416	277.28		B	
NO_x(g/hr)-Tier1 (TL1)	5046	180.30			C

Means that do not share a letter are significantly different.



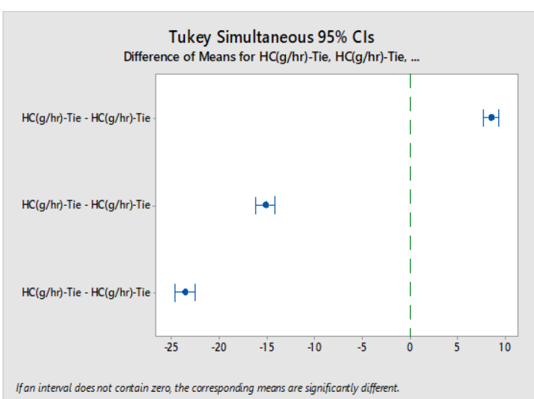


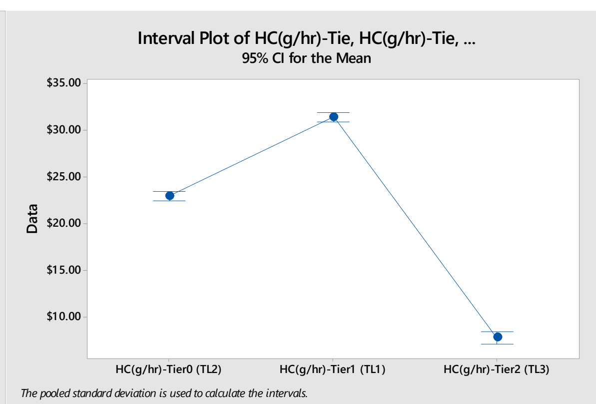
HC(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
HC(g/hr)-Tier1 (TL1)	5046	31.416	A
HC(g/hr)-Tier0 (TL2)	4850	22.978	B
HC(g/hr)-Tier2 (TL3)	2416	7.801	C

Means that do not share a letter are significantly different.



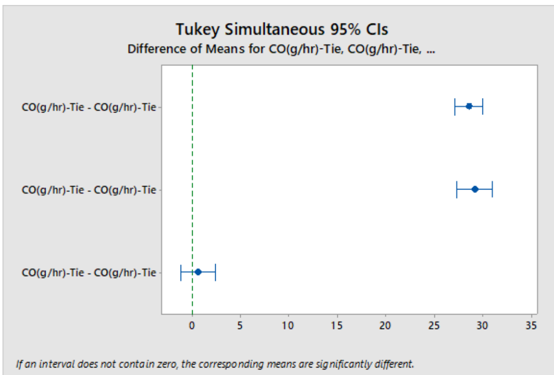


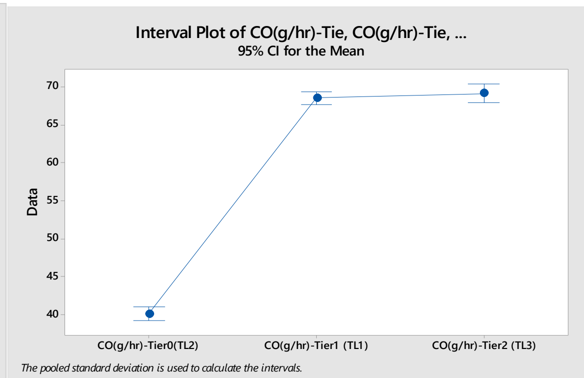
CO(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO(g/hr)-Tier2 (TL3)	2416	69.181	A
CO(g/hr)-Tier1 (TL1)	5046	68.582	A
CO(g/hr)-Tier0(TL2)	4850	40.073	B

Means that do not share a letter are significantly different.



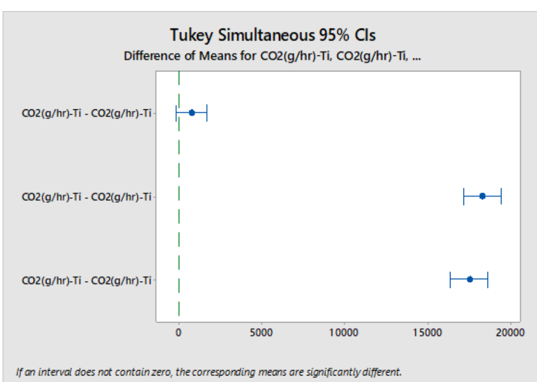


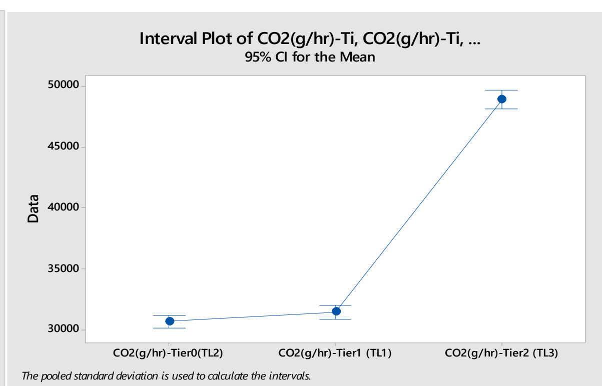
CO_2(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO_2(g/hr)-Tier2 (TL3)	2416	48920	A
CO_2(g/hr)-Tier1 (TL1)	5046	31419	B
CO_2(g/hr)-Tier0(TL2)	4850	30655	B

Means that do not share a letter are significantly different.



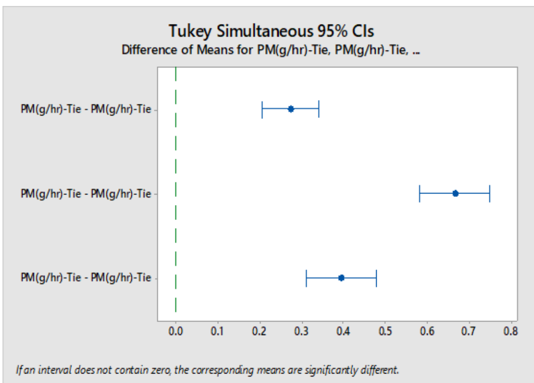


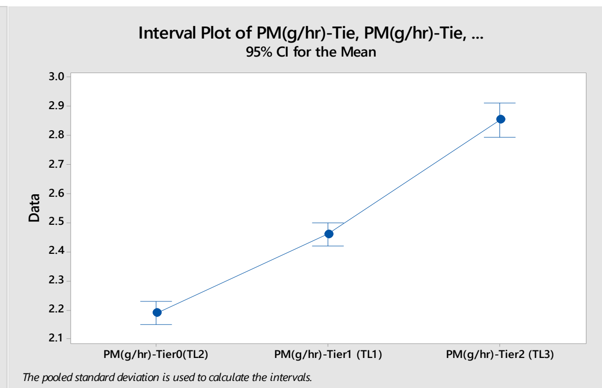
PM(g/hr)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
PM(g/hr)-Tier2 (TL3)	2416	2.8539	A
PM(g/hr)-Tier1 (TL1)	5046	2.4600	B
PM(g/hr)-Tier0(TL2)	4850	2.1881	C

Means that do not share a letter are significantly different.



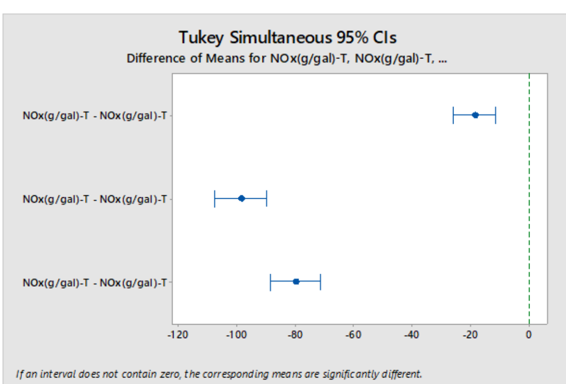


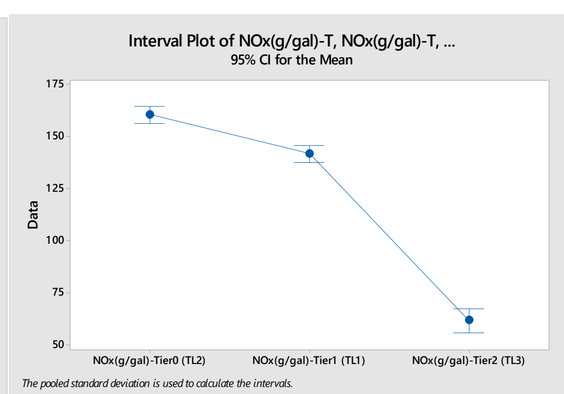
NO_x(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
NO_x(g/gal)-Tier0 (TL2)	4850	160.414	A
NO_x(g/gal)-Tier1 (TL1)	5046	141.61	B
NO_x(g/gal)-Tier2 (TL3)	2416	61.546	C

Means that do not share a letter are significantly different.



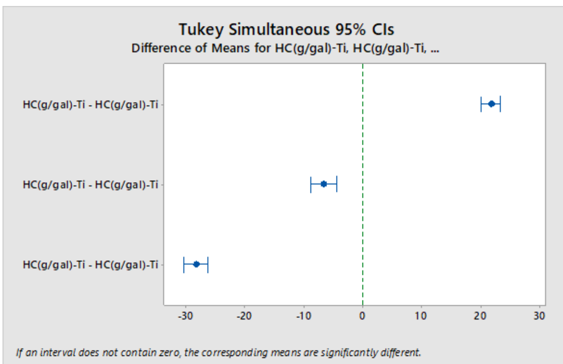


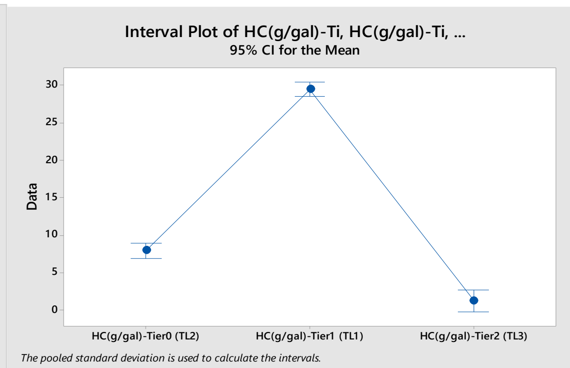
HC(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
HC(g/gal)-Tier1 (TL1)	5046	29.517	A
HC(g/gal)-Tier0 (TL2)	4850	7.8837	B
HC(g/gal)-Tier2 (TL3)	2214	1.1904	C

Means that do not share a letter are significantly different.



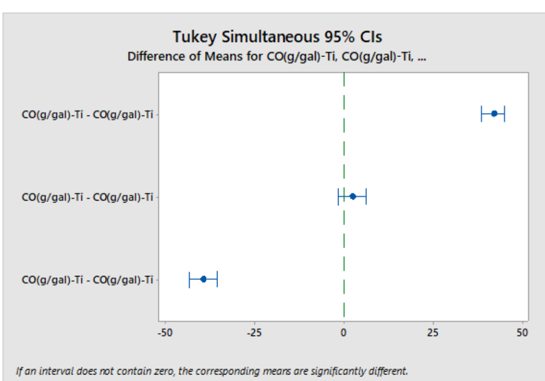


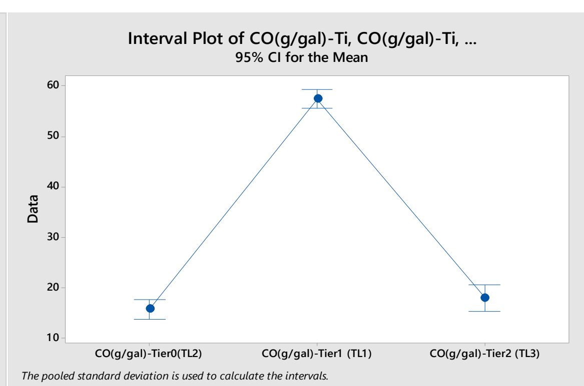
CO (g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO(g/gal)-Tier1 (TL1)	5046	57.45	A
CO(g/gal)-Tier2 (TL3)	2416	17.920	B
CO(g/gal)-Tier0(TL2)	4850	15.6624	B

Means that do not share a letter are significantly different.



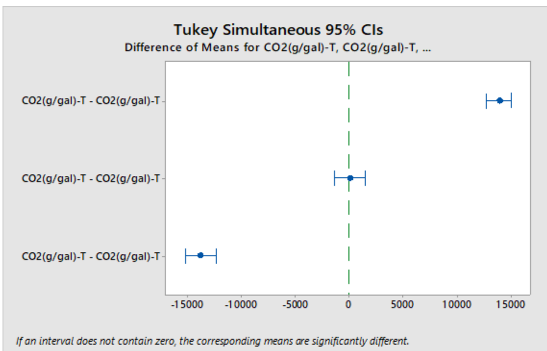


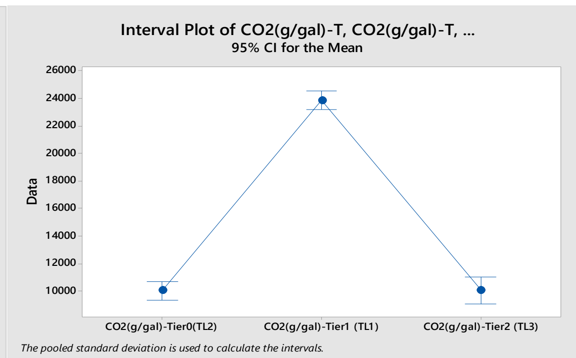
CO_2(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
CO_2(g/gal)-Tier1 (TL1)	5046	23841	A
CO_2(g/gal)-Tier2 (TL3)	2416	10034.8	B
CO_2(g/gal)-Tier0(TL2)	4850	10013.0	B

Means that do not share a letter are significantly different.



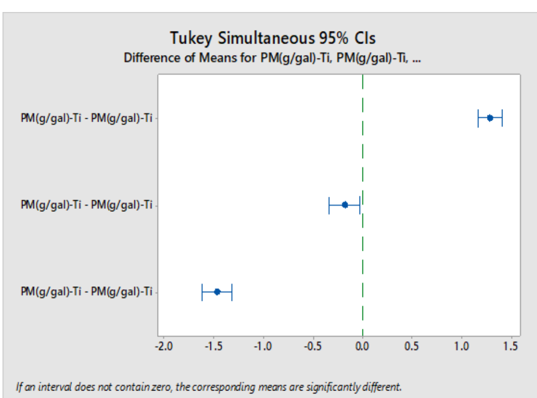


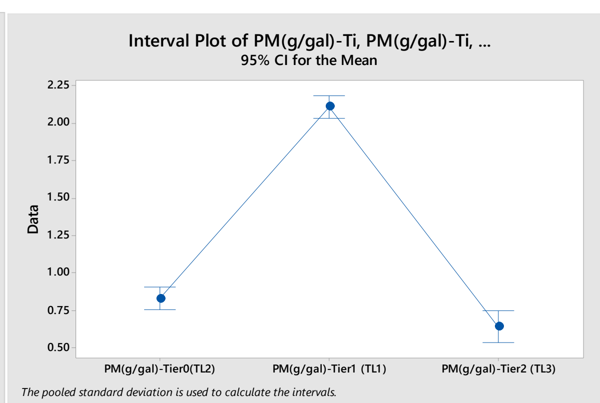
PM(g/gal)

Tukey Pairwise Comparisons

Factor	N	Mean	Grouping
PM(g/gal)-Tier1 (TL1)	5046	2.1095	A
PM(g/gal)-Tier0(TL2)	4850	0.82767	B
PM(g/gal)-Tier2 (TL3)	2416	0.64095	C

Means that do not share a letter are significantly different.





Appendix J

Summary of Equipment Attributes

Equipment	Horsepower (HP)	Displacement (L)	Model Year	Engine Tier
Backhoe 1	88	4.0	2004	2
Backhoe 2	88	4.2	1999	1
Backhoe 3	88	4.2	2000	1
Backhoe 4	97	3.9	2004	2
Backhoe 5	99	4.5	1999	1
Backhoe 6	97	4.5	2004	2
Bulldozer 1	89	5.0	1988	0
Bulldozer 2	95	3.9	2002	1
Bulldozer 3	90	5.0	2003	1
Bulldozer 4	175	10.5	1998	1
Bulldozer 5	285	14.2	1995	0
Bulldozer 6	99	4.2	2005	2
Excavator 1	254	8.3	2001	1
Excavator 2	138	6.4	2003	2
Excavator 3	93	3.9	1998	1
Motor Grader 1	195	8.3	2001	1
Motor Grader 2	195	7.1	2004	2
Motor Grader 3	195	8.3	2001	1
Motor Grader 4	167	8.3	1990	0
Motor Grader 5	160	8.3	1993	0
Off-Road Truck 1	306	9.6	2005	2
Off-Road Truck 2	285	10.3	1998	1
Off-Road Truck 3	285	10.3	1998	1
Track Loader 1	121	7.2	1998	1
Track Loader 2	70	4.5	1997	0
Track Loader 3	127	7.2	2006	2
Wheel Loader 1	149	5.9	2004	2
Wheel Loader 2	130	5.9	2002	1
Wheel Loader 3	130	5.9	2002	1
Wheel Loader 4	126	5.9	2002	1
Wheel Loader 5	133	6.0	2005	2

VITA

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